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INSTITUTE FOR DEFENSE ANALYSES

**Environmental Restoration – Expedient
Methods and Technologies:
A User Guide with Case Studies**

Volume II: Canada and Europe

M. P. Huxley, Principal Researcher
J. F. Kreis, Task Leader
J. E. Tumarkin, Project Leader

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PREFACE

The Institute for Defense Analyses (IDA) compiled this document in support of a NATO Pilot Study for the Committee on the Challenges of Modern Society entitled, "Reuse of Former Military Lands." The pilot study was co-chaired by the Principal Assistant Deputy Under Secretary of Defense for Environmental Security. Originally intended as a guide to methods potentially useful to NATO member nations and Cooperation Partners who desire to convert former military sites to new economic uses, it has wider use in providing planning assistance for site environmental and economic restoration. The Deputy Under Secretary of Defense (Environmental Security) sponsored this work.

Case studies in this volume came from Canada, European NATO member nations, and Partnership for Peace members. They are presented by type of pollution being remediated. Wherever possible, we included more than one site to illustrate each major type of problem, a description of the problem to be resolved, the anticipated cost (if available), and actual cost when known. Also included are discussions of technical problems that have been encountered, source documents containing information that might be useful, and appropriate sites on the World Wide Web that may give summaries of information.

Four previous studies were prepared for the NATO Pilot Study:

- IDA Document D-1936, *Sources of Financial Assistance for the Restoration of Former Military Lands*
- *Project Prospectus for Environmental Restoration*
- IDA Paper P-3383, *Environmental Restoration—Expedient Methods and Technologies: A User Guide With Case Studies, Volume I*
- NATO/CCMS Report # 233, *Handbook on the Reuse of Former Military Lands*.

They are companion pieces to this volume. The four that have now been prepared act as guides that complement one another for planning site restoration and conversion work at former military sites.

The principal researcher and lead author was Mary Pat Huxley. Dr. Joel E. Tumarkin was the project leader; Mr. John F. Kreis was the task leader for this effort. Ms. Susan Clark-Sestak translated the contributions from Russia.

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Defense, Znamenka 17, Moscow, Russia

Sweden

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Numerous restoration case studies have been done in Germany. Due to budgetary restraints, Germany unfortunately could not provide English translations for this document. For German restoration case studies, contact Detlef Grimsky, German Federal Environmental Agency, 14193 Berlin, Bismarckplatz 1, Germany. Tel: 49 30 8903 2266. email: detlef.grimski@uba.de

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I. INTRODUCTION

A. BACKGROUND AND ORGANIZATION

As the second volume¹ of expedient methods and technology case studies, this document summarizes environmental restoration case studies and some technology developments used in environmental restoration of former military lands in Canada, Czech Republic, Hungary, Russia, and Sweden. Our specific purpose is to present technologies that have been used to resolve specific areas of contamination. Only fuel hydrocarbon, chlorinated hydrocarbon, and heavy metal contamination restoration technologies are included. The same contaminants are considered in Volume I.

The sites discussed in this volume usually had a mixture of contaminants. Therefore, if a site had two or three contaminants, it is listed in each relevant contaminant section. Most sites appear more than once. When costs are given, they are listed in both the currency of the country (at the time of the remediation) with a conversion to U.S. dollars to the extent this was possible.

Effectiveness of cleanup in these case studies is not always noted explicitly because of one or more factors. When the studies were received, some site remediation was still in progress, so effectiveness is yet to be determined. Effectiveness of cleanup is sometimes implicit in the data presented; when data indicate levels of contaminant lower than the required standard, effectiveness is assumed even if not stated in the study. Occasionally, the cost of determining effectiveness is prohibitively expensive, so reasonable assumptions are made from site samples along with data from other sites effectively remediated with the same technology.

This document is organized in chapters by contaminant. In each section, as far as possible, we illustrate examples of contamination, the extent of contamination, the media in which contaminants were found (soil, sand, clay, water, sediment, etc.), the anticipated cost of remediation, the final cost of remediation (if available), and the success of the

¹ *Environmental Restoration—Expedient Methods and Technologies: A User Guide with Case Studies*, Volume 1, IDA Paper P-3383, compiled Department of Defense, Department of Energy, and EPA restoration sites in the United States.

remediation technique at that site. By providing this information, it is our hope that others may be able to better prepare their own plans to resolve similar problems.

B. DENSITY, CHEMISTRY, LOCATION, AND MICROORGANISM METABOLISM

Technology designs for the remediation of fuels, chlorinated solvents, and heavy metals are driven by three factors: the density and chemistry of the compound, where it is located as a contaminant, and whether or not microorganisms can use it as either a nutrient or an electron acceptor.

1. Density and Chemistry

Fuels, also known as light non-aqueous phase liquids (LNAPLs), are less dense than water and thus float on water and vaporize to some extent: petrol vaporizes well; diesel and jet fuels, less well; others, such as lubricants and polyaromatic hydrocarbons (PAHs), not at all. PAHs range in solubility from somewhat soluble to not soluble; some PAHs are solid at ambient temperatures. Chlorinated solvents (also called chlorinated hydrocarbons) are hydrocarbons with one or more chlorine atoms. Most chlorinated solvents are also denser than water and thus are often referred to as dense non-aqueous phase liquids (DNAPLs). However, some DNAPLs are not chlorinated, and a few chlorinated solvents are less dense than water. DNAPLs and chlorinated solvents are sometimes referred to in the literature as being an equivalent group of chemicals. One should bear in mind that they are not quite the same.

2. Location

Contaminants can be in water or soil: in surface water, on the groundwater table, dissolved in the groundwater, or in soil zones; in surface soil, in subsurface soil that is not saturated with water (vadose zone), or in subsurface soil that is saturated with water (saturated zone). The saturated zone contains the groundwater. However, groundwater can be pumped out of the saturated zone, leaving contaminant still in the soil of the saturated zone and dissolved in the remaining water.

3. Microorganism Metabolism of Contaminants

Microorganisms that degrade fuel hydrocarbons are everywhere. Some researchers speculate that this is due to the presence of crude oil deposits and seeps worldwide. Regardless of their origin, such microorganisms can be used effectively as

restoration agents. The rate of biodegradation depends on the water solubility of the fuel components and the type of electron acceptor present. Water-soluble components of fuel and straight-chain alkanes are readily degraded under aerobic conditions, whereas polyaromatic hydrocarbons, other than benzene, toluene, ethylbenzene, and meta-, ortho-, and paraxylenes (BTEX), are degraded less rapidly or not at all. Anaerobic degradation of BTEX occurs slowly.

Microbial degradation of chlorinated solvents is problematic and does not readily occur using chlorinated solvents as a primary source of microbial energy. Chlorinated solvents under anaerobic conditions may be reductively dechlorinated, and under aerobic conditions, enzyme systems in operation on other chemicals fortuitously degrade chlorinated solvents in a process called co-metabolism. Microorganisms that reductively dechlorinate and co-metabolize are everywhere, but the processes are slow. Reductive dechlorination occurs under sulfate-reducing and methanogenic conditions, which offers least favorable yield of energy to a microorganism. Co-metabolism is slow, and organisms apparently derive no growth-linked or energy-conserving benefit from the process.

Microbial degradation of heavy metals does not occur, but microorganism enzymes can change the valence state of metals. This change affects the bioavailability of the metal, sometimes increasing it and sometimes decreasing it, depending on the metal.

Table 1, Summary of Findings and Index to the Cases, summarizes information collected for the major types of contamination covered in this document. The table is intended for use as a quick reference guide for readers who wish to find specific problems and related treatments.

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Table 1. Summary of Findings and Index to the Cases

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases
Fuel Hydrocarbons—Case Studies				
Soil & Water	Drinking Water	<i>Ex-situ</i> biodegradation, groundwater pumping, venting, hydraulic barriers	Ch. II p. 20	Site 1—Milovice - tábor (Milovice camp) Central Bohemia, Czech Republic—Five sites in one city: oil storage (DNAPLs and LNAPLs), three garages (LNAPLs), and a building used for dry cleaning of clothing (DNAPLs). Hydrocarbon contamination varies from 100 mg/kg soil to 10,000 mg/kg soil. Cleanup planned until 2005, then 2 years of monitoring. Total estimated cost from 1998-2007 is CK 86 million (US\$ 2.4million).
Soil (Saturated & Unsaturated Zone)	Drinking Water, River	Pumping, venting, bioventing, air sparging	Ch. II p. 23	Site 2—Air Base Hradčany , in Ralsko, northern Bohemia, Czech Republic—Former military base had tanks, pipes, and so forth for supplying fuel, so the site has LNAPLs and also DNAPLs. Hundreds of hectares are contaminated. Site cleanup costs are included in general figures for the Czech Republic, which are estimated at CK 890 million (US\$ 29 million) for site investigation and risk assessment, and is expected to be about CK 1.3–1.4 billion (US\$ 50 million) for decontamination of groundwater, soil, and removal of dumps.
Soil (Saturated & Unsaturated Zone)	Drinking Water	Pumping, venting, biodegradation	Ch. II p. 26	Site 3—Milovice Air Base Boží Dar , Central Bohemia, 30 km north of Prague, Czech Republic—The area is contaminated with both LNAPLs and DNAPLs. The former military base had a fuel infrastructure of tanks, pipes, and pipelines, as well as garages, workshops, stores, chemical cleaning facilities, army barracks, and houses for military personnel and their families. Site cleanup costs are included in general figures for the Czech Republic, which are estimated at CK 890 million (US\$ 29 million) for site investigation and risk assessment, and is expected to be about CK 1.3–1.4 billion (US\$ 50 million) for decontamination of groundwater, soil and removal of dumps.
Soil (Saturated & Unsaturated Zone)	Drinking Water	Pumping, venting	Ch. II p. 28	Site 4—Olomouc – Nefedín , central Moravia, Czech Republic—Hundreds of hectares in a former helicopter base with army barracks are contaminated with fuels and chlorinated solvents. Site cleanup costs are included in general figures for the Czech Republic, which are estimated at CK 890 million (US\$ 29 million) for site investigation and risk assessment, and is expected to be about CK 1.3-1.4 billion (US\$ 50 million) for decontamination of groundwater, soil, and removal of dumps.
Soil (Saturated & Unsaturated Zone)	Drinking Water, Brook	Pumping, <i>ex situ</i> biodegradation, venting	Ch. II p. 28	Site 5—Zákupy , Village Nové Zákupy, near Kuřívody, Czech Republic—POL storage began in a sandstone quarry in the 1970s. The contaminated area is about one hectare. Site cleanup costs are included in general figures for the Czech Republic, which are estimated at CK 890 million (US\$ 29 million) for site investigation and risk assessment, and is expected to be about CK 1.3–1.4 billion (US\$ 50 million) for decontamination of groundwater, soil, and removal of dumps.

Table 1. (Continued)

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases
Fuel Hydrocarbons—Case Studies (continued)				
Soil & Groundwater	Drinking Water	Soil vapor extraction, air injection, well blasting, pump and treat, air stripping, activated carbon filters.	Ch. II p. 29	<p>Site 6—Jirice Base, District of Mladá Boleslav, Central Bohemia, Czech Republic— Contamination was greatest at Camp No. 19 (800 x 900 meters), from a parking lot for trucks and combat vehicles, workshops, and 20 underground fuel storage tanks for diesel and petrol with a total capacity of 1,240 m³. A large firing range (750 x 500 meters) was situated close to Camp No. 19. In addition to fuel contamination, hot spots of chlorinated hydrocarbon contamination were found in the groundwater and vadose zone. Trichloroethylene (TCE) and tetrachloroethylene (PCE) were the main contaminants at this site, exceeding Czech limits in groundwater (TCE 50µg/L, PCE 10 µg/L). A few wells also had zinc concentrations (maximum 2,200 mg Zn/L) exceeding the limit of 5 mg/L. Remediation of groundwater was based on pumping and treating from 5-8 wells, then treating by air stripping in three towers and activated carbon filters. Condensed chlorinated solvents were burned off-site. The cleaned water was recharged totally on the outskirts of the contaminated plume either via sprinklers on the ground surface or by injection into infiltration wells. During remediation 2 kg of oil hydrocarbons and 249 kg of chlorinated hydrocarbons (mostly PCE and TCE) were removed. Water containing high concentrations of zinc was pre-treated with the help of a zeolite filter. The remediation started in 1993 and was finished in 1998. The total cost of groundwater remediation, including quality monitoring, was CK 9.2 million (US\$ 247,000).</p> <p>Remediation of unsaturated zone was based on soil vapor extraction (SVE), air injection, and well blasting. The SVE system was operated from February 1995 to December 1998. The system was shut off when CHC concentrations declined repeatedly below Czech standards (individual CHC 10 mg/m³) or when the removal rate was lower than 5 kg of volatile contaminant per month. During soil vapor extraction, 285 kg of oil hydrocarbons and 1,610 kg of chlorinated aliphatic hydrocarbons were extracted. An estimated 5,000-10,000 kg of oil hydrocarbons were decomposed by microbial activity during soil vapor extraction and air injection, according to a rise of CO₂ content in the exhausted soil air and its comparison with the soil air in clean parts of the unsaturated zone. The total cost of soil vapour extraction was CK 4.7 mil (US\$ 130,000).</p>

Table 1. (Continued)

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases	
				Fuel Hydrocarbons—Case Studies (continued)	
Soil & Groundwater	Drinking Water	Bioremediation, pump and treat, air stripping (SVE)	Ch. II p. 33	<p>Site 7—Hvezdov, northern Bohemia about 80 km north of Prague, near the town of Mimon—This 15 km² area is contaminated with both LNAPLs and DNAPLs. LNAPLs are from motor pools, vehicle repair sites, oil storage and coal stocks, oil transformers, and petrol stations, and DNAPLs are from extinguishing military rocket launchers. In the unsaturated zone, soils with LNAPL concentrations over cleanup limits were removed from the environment and biodegraded in special biodegradation fields. Soil vapor extraction methods extracted significant amounts of volatile aromatic and chlorinated hydrocarbons. In the saturated zone, groundwater pumping, followed by stripping and filtration, intercepted the contaminant plume at two locations; pumping also functioned as a hydraulic barrier to help protect the water quality. 1990-1991—site investigation: CK 3.7million (US\$ 100,000). Remediation from 1991-1995—about CK 25.9 million (US\$ 700,000) total.</p>	
Soil & Groundwater	Drinking Water	Bioremediation, pump and treat, air stripping (SVE)	Ch. II p. 34	<p>Site 8—Lustenice, in central Bohemia near the town Benatky and Jizerou, about 30 km north of Prague, and between other Soviet military sites (Milovice, Jirice, and Bozi Dar to the south)—Used as a military site since before 1918, this 3.5 km² site is contaminated with both LNAPLs and DNAPLs to a depth of 30 meters from motor pools, vehicle repair sites, oil storage, oil transformers, petrol stations, and a chemical cleaning and laundry facility. Bioremediation of soils for LNAPL cleanup and air stripping of DNAPLs yielded about 100 tons LNAPLs and 5 tons of chlorinated hydrocarbons. Costs were 1990-1991—site survey stage) CK 11.1 million (US\$ 300,000); 1991-1995—about CK 518 million (US\$ 1,400,000) total.</p>	
Soil & Groundwater	Drinking Water	Pump and treat, air stripping	Ch. II p. 36	<p>Site 9—Tököl Air Base, NW side of Csepel Island, 25 km south of Budapest, Hungary—In 1991, approximately 2,200 m³ of jet fuel from storage tanks were found to contaminate ground and groundwater. The contamination was in the hydrogeological protective zone of Halásztelek well field, which supplies Budapest with 60,000 m³ of potable water per year. The aim of first-stage remediation was to stop spreading free phase CH and dissolved hydrocarbons in groundwater, so these were pumped out. Air stripping removed dissolved jet fuel components in pumped groundwater. The goal for the stripping was 100 µg/l total hydrocarbons. Some treated groundwater was recycled into a total 35 injection wells; some treated groundwater (400–500 m³/day) was pumped into the Danube River. Oil skimmers and scavenger pumps did free-phase CH recovery. First-stage remediation started on 10 December 1992 and lasted until 30 June 1993. During this period, 1980 m³ of free phase jet fuel and 1.8 million m³ of water contaminated with dissolved CH groundwater were recovered from the ground. The cost of the project was Hungarian Forint 200 million (US\$ 1.0 million).</p>	

Table 1. (Continued)

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases
Fuel Hydrocarbons—Case Studies (continued)				
Soil & Groundwater	Drinking Water	Bio-Cell, soil vapor extraction	Ch. II p. 38	<p>Site 10—Canadian Forces Base Borden, Ontario, Canada—Hydrocarbons (gasoline) resulting from leaking underground storage tanks were found as free product at the site, contaminating soil and groundwater. About 3 meters of clean soil lay above the 2.5-meter-thick hydrocarbon-impacted layer. The clean soil was excavated and set aside; contaminated soil was excavated and stockpiled on liners. Clean soil was then brought back in and leveled to the normal groundwater elevation. Plastic liner, sumps, leachate, and soil vapor extraction systems were installed.</p> <p>The SVE's off-gases were treated on-site using a catalytic oxidizer. Excavation was approximately 40 x 70 x 6 meters (17,000 m³). Initially, TPH and BTEX concentrations were in excess of 14,000 ppm and 1,000 ppm respectively for soil. After approximately 7 months of operation, concentrations were below Provincial Environment Ministry's guidelines for industrial sites and, in most cases, below detection level. Positive results indicate that natural attenuation program has been successful in stopping contaminant plume. The catalytic oxidizer treated the equivalent of 1,100 liters of gasoline. The site was decommissioned in September 1999. Cost data not included.</p>
Soil & Groundwater	Drinking Water, School	Bioventing, vapor extraction system (air sparging, soil vapor extraction, bioventing, and off-gas treatment using a biofilter)	Ch. II p. 40	<p>Site 11—Canadian Forces Base Petawawa, Canada—Fuel from underground storage tanks leaked about 6,000 liters into groundwater. The plume, covering about 1,000 m², extended under a road and onto a school property. Due to water depth, <i>in-situ</i> remediation methods included free product removal by bioslurping, oil-water separator, a granular activated carbon (GAC) unit for contaminated water treatment; a vapor extraction system (VES) was commissioned in December 1996, which included a combination of air sparging, soil vapor extraction, bioventing, and off-gas treatment using a biofilter. The added benefit of VES eliminated residual hydrocarbons within the 1-year timeframe predicted, and the site along with its groundwater were declared clean in October 1999. Cost data not included.</p>
Soil	Drinking Water	Landfarming	Ch. II p. 42	<p>Site 12—Landfarm, Canadian Forces Base Borden, Canada—A landfarm was built at CFB Borden in 1994 to accommodate impacted soils recovered during the excavation of fuel storage tanks. Surface area is approximately 560 m² (5,000 ft²) and soil is placed in lifts of 0.67 meters (2 feet) in thickness. The landfarm had limited success at its inception due to inadequate drainage system, incorrect surface drainage slopes, irregular tilling schedule, incorrect construction that left gaps in the geomembrane liner in the berms, and erosion of the berms. In 1998, berms were repaired, drainage system improved, and fertilizer added to stimulate microbial growth. The landfarm is now being operated successfully. Cost data not included.</p>

Table 1. (Continued)

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases	
				Fuel Hydrocarbons—Case Studies (continued)	
Soil	Drinking Water	Landfarming	Ch. II p. 43	<p>Site 13—Landfarm, Lancaster Park, Canadian Forces Base Edmonton, Alberta, Canada—Approximately 20,000 m³ of soil was contaminated with JP-4 jet fuel while upgrading a former bulk fuel storage area housing four above-ground storage tanks. This landfarm used a clay liner, and covered 9,000 m² of surface area. Moisture, pH, nutrient, and leachate are controlled, as is the filling operation. The goal is to decrease concentrations of hydrocarbon components below provincial guidelines for industrial/commercial land use. The vapor inhalation pathway to human beings is the primary consideration with guidelines as follows: Benzene—1.5 ppm; Toluene—340 ppm; Ethylbenzene—400 ppm; Xylenes—130 ppm; Total Petroleum Hydrocarbons (Purgeables and Extractables)—4000 ppm. These levels are typically attained within a 7-10 day period at the Lancaster Park landfarm. Contaminant volatilization plays a key role in lowering the concentration measured from soil samples. Alberta does not have air emissions guidelines for these situations. Cost data not included.</p>	
Soil	Test Plot	Bioventing, <i>in situ</i> bioremediation	Ch. II p. 45	<p>Site 14—Air Force Unit, Ängelholm, Sweden, JP-4 Jet Fuel Spill—Test plot of 200 m² to demonstrate bioventing and <i>in situ</i> bioremediation. JP-4 concentrations varied: hydrocarbons tested from headspace of collected soil samples. Nutrients and microorganisms added to site. Demonstrated bioremediation. Estimated cost US\$ 20/ m³ or US\$ 12/ton.</p>	
Soil	Water	Soil flushing, <i>in situ</i> bioremediation	Ch. II p. 47	<p>Site 15—Saskatchewan, Canada, Soil Flushing of a Remote Boreal Forest Diesel Spill—A spill of more than 2,000 gallons of diesel occurred on a remote crown-land location. The diesel contamination spread into a gravel pad underneath a building and off site into neighboring vegetation. Diesel fuel reached a depth of 3 feet and levels in excess of 20,000 ppm on site. The off-site area had concentrations in excess of 18,000 ppm. The path of the spill was flushed with a water/surfactant mixture three times, followed by a fertilizer/water flush to encourage microbial growth. Surface soil was also sprinkled with fertilizer by hand. BTEX levels in soil samples were below detectable levels. In the offsite contaminated areas, TPH was 18,000 ppm before treatment and 800 ppm after treatment. Cost data not included.</p>	

Table 1. (Continued)

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases
Fuel Hydrocarbons—Case Studies (continued)				
Groundwater & Soil	Water	Air sparging with a gas liquid reactor	Ch. II p. 49	Site 16—Canadian Forces Base Trenton —A former service station site was contaminated with BTEX from leaking underground storage tanks. Previous soil remediation and source removal had limited efficiency because most of contaminated material was under service station structure. The objective was to demonstrate effectiveness of the Gas Liquid Reactor (GLR) unit to add oxygen to groundwater, stimulating bacterial activity and reducing BTEX and hydrocarbons. The GLR produces microbubbles (diameter 5-50 microns), maximizing mass transfer area between the gas and liquid phase to increase efficiency of gas to liquid transfer. Samples taken from on-site monitoring wells showed that bacterial activity increased significantly after GLR infused air into the groundwater, with a corresponding decrease in BTEX and petroleum hydrocarbons. Cost data not included.
Groundwater & Soil	Water	Natural Attenuation	Ch. II p. 50	Site 17—Canadian Forces Support Unit Former Fire Fighting Training Area, Ontario, Canada —Jet Fuel Natural Attenuation Project—This 1995 study at a former fire-fighting training area (FFTA) at an airport included site characterization, contaminant distribution, evaluation of natural attenuation as a remedial option for hydrocarbon (jet fuel) impacted groundwater, applications of computer modeling, and a quantitative risk assessment. The FFTA was used almost 25 years and closed in 1992. Approximately four burns per month were completed with as much as 3,500 liters of jet fuel were sprayed and burned. Up to 160,000 liters of jet fuel were used yearly without a fuel collection system. Biodegradation of BTEX/TPH parameters by indigenous subsurface microbes appears to be primary mechanism for attenuation and mass loss at documented sites. Monitoring the site in 1995 and 2000 showed continued biodegradation by both aerobic and anaerobic mechanisms. BIOPLUME modeling has shown that impacts to the environment will decrease significantly over the next 10 years. Cost data not included.
Soil	Water	Low Temperature Thermal Desorption	Ch. II p. 55	Site 18—Canadian Forces Base Cold Lake, Alberta, Canada —Low Temperature Thermal Desorption of Fuel Hydrocarbon and Chlorinated Solvents Contaminated Soil—Approximately 9,300 metric tons of contaminated soil was remediated in March and April 1998. Soil was contaminated with petroleum hydrocarbons, ethylene glycol, trichloroethylene, and phenol, which had been stockpiled in various locations. Soil was treated with a mobile Low Temperature Thermal Desorption (LTTD) technology, which was located beside one of the stockpiles. The system operated on a 24-hour-per-day schedule without disturbance to surrounding military operations. Cost data not included.

Table 1. (Continued)

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases
Fuel Hydrocarbons—Pilot Scale/Demonstrations				
Soil & Water	Water	Transport and recultivation	Ch. II p. 56	Site 1—Valdaisky State National Park, Russia —Technology developed to remediate territory contaminated with heavy oil products (fuel oil) and experimentally test it during environmental restoration of Valdaisky State National Park in areas where troop units had been stationed. Contaminated soils removed and transported to a recultivation area (beyond the borders of the military town), along with remediation of soils and reservoirs <i>in situ</i> (in the military town). Cost to date: 180,000 rubles (US\$ 64,000).
Soil	N/A	Development of technologies and methods	Ch. II p. 57	Site 2—Engels Air Force Base, Russia — <i>Developing Probes and Technologies to Detect, Monitor and Extract Fuel Oil Products from Soil</i> —The objective is to create a maximally effective complex of analytical and manufactured technologies for detecting, monitoring, and eliminating oil product contamination. Plans have been developed for LNAPL remediation technologies. Cost data to December 1999: 850,000 rubles (US\$ 30,000).
Soil	N/A	Integrated method for assessment	Ch. II p. 59	Site 3—General Use on Military Bases in Russia —An integrated method is being developed for assessing environmental ground conditions where ground, missile, and air force troops and sailors are stationed, along with methods for improving such conditions. Tasks: use mathematical models, issue standard methods for monitoring missile fuel, explosives, and artillery gunpowder in the soil and water, create systematic recommendations and compile a package of standardized technical documents, necessary for carrying out environmental inspections and remediation of military garrisons in Arctic conditions. Statements of work have been completed and field tests have been done. Cost to December 1999: 1.9 million rubles (US\$ 67,000).
Soil & Water	N/A	Mobile POL cleanup unit	Ch. II p. 61	Site 4—General Use on Military Bases in Russia —Substantiate ways of creating a mobile, standardized, automated production complex using nonwaste generating technology for POL cleanup of territories and internal water areas. Completed tasks through December 1998: selected research areas, methods, leaders, and mathematical models (some experimental research); defined list of priority contaminants; determined method for monitoring and recommendations for cleanup; synthesized and evaluated research results. Cost data not included.

Table 1. (Continued)

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases	
				Fuel Hydrocarbons—Pilot Scale/Demonstrations (continued)	
Soil	N/A	Funnel and gate	Ch. II p. 63	<p>Site 5—Canadian Forces Base Borden, Canada—Pilot Scale Funnel and Gate for Naphthalene Plume Control—In 1990, coal tar creosote was placed below water table in sand aquifer to create a dissolved phase plume. Phenolics and xylenes were removed by natural attenuation, but naphthalene plume continued to expand. A pilot-scale Funnel & Gate (F&G) was installed in 1997 to limit naphthalene-plume expansion. The F&G was a Waterloo Barrier™ sealable sheet piling. The gate makes use of a novel cassette system with four removable sections. Surprisingly, aerobic naphthalene degradation is sufficient for complete attenuation even before the cassette gate treatment. Additional field sampling is underway to evaluate this idea. Evaluation of the predicted migration of naphthalene around the funnel continues. Cost data not included.</p>	
Soil	N/A	Electron-Thermal Dynamic Stripping	Ch. II p. 64	<p>Site 6—Canadian Forces Base Calgary—Electron-Thermal Dynamic Stripping Pilot Test of Fuel Hydrocarbons—Between February and June 1999, a pilot test of an <i>in situ</i> fuel hydrocarbon remediation process, Electro-Thermal Dynamic Stripping (ETDS), was carried out at a service station. The test area was 315 m² and the average thickness of soil affected with petroleum hydrocarbons was approximately 1.5 meters at a depth of 4.2 meters below grade. ETDS increased subsurface soil temperature by resistance heating by passing an electric current through saturated soil, resulting in enhanced volatilization of organic compounds. Thus, organic chemical compounds were more easily desorbed from soils; a dual-phase extraction (or bioslurping) process was used for vapor and liquid recovery. The average benzene concentration in March 1999 samples was 4 mg/kg; in April/May 1999 samples was 3.7 mg/kg; and in June 1999 samples was 1.7 mg/kg. Data evaluation suggests a reduction in the mass of benzene of approximately 73% during the pilot test. Cost data not included.</p>	
Soil	N/A	Vacuum-enhanced recovery	Ch. II p. 67	<p>Site 7—Canadian Forces Base Calgary, Alberta, Canada—Vacuum-Enhanced Liquid Recovery Pilot Test—In 1997, a pilot test was performed at a former CANEX service station as part of a series of tests to estimate feasibility of various <i>in-situ</i> remediation techniques beneath the site. Drawdown rates in only two of twenty-two boreholes are given. Cost data not included.</p>	

Table 1. (Continued)

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases	
				Chlorinated Solvents—Case Studies	
Soil & Water	Drinking Water	Ex-situ biodegradation, ground water pumping, venting, hydraulic barriers	Ch. III p. 73	Site 1—Central Bohemia, Czech Republic —Five sites in one city: oil storage (DNAPLs and LNAPLs), three garages (LNAPLs), and a building used for dry cleaning of clothing (DNAPLs). Hydrocarbon contamination varies from 100mg/kg soil to 10,000 mg/kg soil. Cleanup planned until 2005, then 2 years of monitoring. Total estimated cost from 1998-2007 is CK 86 million (US\$ 2.4million).	
Soil (Saturated & Unsaturated Zone)	Drinking Water, River	Pumping, venting, bioventing, air sparging	Ch. III p. 75	Site 2—Air Base Hradčany, in Ralsko, northern Bohemia, Czech Republic —Former military base had tanks, pipes, and so forth for supplying fuel, so the site has LNAPLs and also DNAPLs. Hundreds of hectares are contaminated. Site cleanup costs are included in general figures for the Czech Republic, which are estimated at CK 890 million (US \$25 million) for site investigation and risk assessment, and is expected to be about CK 1.3–1.4 billion (US\$ 38–40 million) for decontamination of groundwater, soil, and removal of dumps.	
Soil (Saturated & Unsaturated Zone)	Drinking Water	Pumping, venting, biodegradation	Ch. III p. 79	Site 3—Milovice Air Base Boží Dar, Central Bohemia, 30 km north of Prague, Czech Republic —The area is contaminated with both LNAPLs and DNAPLs. The former military base had a fuel infrastructure of tanks, pipes, and pipelines, as well as garages, workshops, stores, chemical cleaning facilities, army barracks, and houses for military personnel and their families. Site cleanup costs are included in general figures for the Czech Republic, which are estimated at CK 890 million (US \$25 million) for site investigation and risk assessment, and is expected to be about CK 1.3–1.4 billion (US\$ 38–40 million) for decontamination of groundwater, soil and removal of dumps.	
Soil (Saturated & Unsaturated Zone)	Drinking Water	Pumping, venting	Ch. III p. 80	Site 4—Olomouc – Neředín, central Moravia, Czech Republic —Hundreds of hectares in a former helicopter base with army barracks are contaminated with fuels and chlorinated solvents. Site cleanup costs are included in general figures for the Czech Republic, which are estimated at CK 890 million (US \$25 million) for site investigation and risk assessment, and is expected to be about CK 1.3–1.4 billion (US\$ 38–40 million) for decontamination of groundwater, soil, and removal of dumps.	
Soil	Drinking Water, Brook	Pumping, venting	Ch. III p. 80	Site 5—Zákupy, Village Nové (New) Zákupy, near Kuřivody, Czech Republic—POL storage began in a sandstone quarry in the 1970s. The contaminated area is about one hectare. Site cleanup costs are included in general figures for the Czech Republic, which are estimated at CK 890 million (US \$25 million) for site investigation and risk assessment, and is expected to be about CK 1.3–1.4 billion (US\$ 38–40 million) for decontamination of groundwater, soil, and removal of dumps.	

Table 1. (Continued)

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases
Chlorinated Solvents—Case Studies (continued)				
Soil & Groundwater	Drinking Water	Pump and treat, air stripping, activated carbon filters	Ch. III p. 81	<p>Site 6—Jirice Base, District of Mladá Boleslav, Central Bohemia, Czech Republic— Contamination was greatest at Camp No. 19 (800 x 900 meters), from a parking lot for trucks and combat vehicles, workshops, and 20 underground fuel storage tanks for diesel and petrol with a total capacity of 1,240 m³. A large firing range (750 x 500 meters) was situated close to Camp No. 19. In addition to fuel contamination, hot spots of chlorinated hydrocarbon contamination were found in the groundwater and vadose zone. Trichloroethylene (TCE) and tetrachloroethylene (PCE) were the main contaminants at this site, exceeding Czech limits in groundwater (TCE 50 µg/L, PCE 10 µg/L). A few wells also had zinc concentrations (maximum 2,200 mg Zn/L) exceeding the limit of 5 mg/L. Remediation of groundwater was based on pumping and treating from 5-8 wells, then treating by air stripping in three towers and activated carbon filters. Contaminated chlorinated solvents were burned off-site. The cleaned water was recharged totally on the outskirts of the contaminated plume either via sprinklers on the ground surface or by injection into infiltration wells. During remediation 2 kg of oil hydrocarbons and 249 kg of chlorinated hydrocarbons (mostly PCE and TCE) were removed. Water containing high concentrations of zinc was pre-treated with the help of a zeolite filter. The remediation started in 1993 and was finished in 1998. The total cost of groundwater remediation, including quality monitoring, was CK 9.2 million (US\$ 247,000).</p> <p>Remediation of unsaturated zone was based on soil vapor extraction (SVE), air injection, and well blasting. The SVE system was operated from February 1995 to December 1998. The system was shut off when CHC concentrations declined repeatedly below Czech standards (individual CHC 10 mg/m³) or when the removal rate was lower than 5 kg of volatile contaminant per month. During soil vapor extraction, 285 kg of oil hydrocarbons and 1,610 kg of chlorinated aliphatic hydrocarbons were extracted. An estimated 5,000-10,000 kg of oil hydrocarbons were decomposed by microbial activity during soil vapor extraction and air injection, according to a rise of CO₂ content in the exhausted soil air and its comparison with the soil air in clean parts of the unsaturated zone. The total cost of soil vapour extraction was CK 4.7 million (US\$ 130,000).</p>

Table 1. (Continued)

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases
Chlorinated Solvents—Case Studies (continued)				
Soil & Groundwater	Drinking Water		Ch. III p. 85	Site 7—Hvezdov , northern Bohemia about 80 km north of Prague, near the town of Mimon. This 15 km ² area is contaminated with both LNAPLs and DNAPLs. LNAPLs are from motor pools, vehicle repair sites, oil storage and coal stocks, oil transformers, and petrol stations, and DNAPLs are from extinguishing military rocket launchers. In the unsaturated zone, soils with LNAPL concentrations over cleanup limits were removed from the environment and biodegraded in special biodegradation fields. Soil vapor extraction methods extracted significant amounts of volatile aromatic and chlorinated hydrocarbons. In the saturated zone, groundwater pumping, followed by stripping and filtration, intercepted the contaminant plume at two locations; pumping also functioned as a hydraulic barrier to help protect the water quality. 1990-1991—site investigation: CK 3.7 million (US\$ 100,000). Remediation from 1991-1995—about CK 25.9 million (US\$ 700,000) total.
Soil & Groundwater	Drinking Water	Bioremediation, pump and treat, air stripping (SVE)	Ch. III p. 87	Site 8—Lustenice , in central Bohemia near the town Benatky and Jizerou, about 30 km north of Prague, and between other Soviet military sites (Milovice, Jirice, and Bozi Dar to the south). Used as a military site since before 1918, this 3.5 km ² site is contaminated with both LNAPLs and DNAPLs to a depth of 30 meters from motor pools, vehicle repair sites, oil storage, oil transformers, petrol stations, and a chemical cleaning and laundry facility. Bioremediation of soils for LNAPL cleanup and air stripping of DNAPLs yielded about 100 tons LNAPLs and 5 tons of chlorinated hydrocarbons. Costs were 1990-1991—site survey stage) CK 11.1 million (US\$ 300,000); 1991-1995—about CK 518 million (US\$ 1,400,000) total.
Soil	Drinking Water, Air	Incineration	Ch. III p. 88	Site 9—Canadian Forces Base Goose Bay, Canada—PCB-Materials Incineration —The first use of a mobile PCB incinerator was at Goose Bay in 1989 to destroy approximately 3,500 tons of PCB contaminated materials. Though mostly PCB contaminated soil from transformer spills at abandoned radar sites in Labrador, the materials included transformer carcasses, containers, and wood products above the 50 ppm PCB that defines hazardous waste. Incineration option was selected by steering committee formed of citizens from the town of Happy Valley-Goose Bay, as well as the DND, Environment Canada, and the Newfoundland Department of Environment and Lands. Materials were shredded before incineration. The temperature of the first of two chambers was 1,000 °C, and the second chamber 1,200 °C. Incineration achieved a destruction and removal efficiency of 99.999% for the soils. Cost data not included.

Table 1. (Continued)

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases
Chlorinated Solvents—Case Studies (continued)				
Soil	Water	Low Temperature Thermal Desorption	Ch. III p. 91	Site 10—Canadian Forces Base Cold Lake, Alberta, Canada—Low Temperature Thermal Desorption of Fuel Hydrocarbon and Chlorinated Solvents Contaminated Soil —Approximately 9,300 metric tons of contaminated soil was remediated in March and April 1998. Soil was contaminated with petroleum hydrocarbons, ethylene glycol, trichloroethylene, and phenol, which had been stockpiled in various locations. Soil was treated with a mobile Low Temperature Thermal Desorption (LTTD) technology, which was located beside one of the stockpiles. The system operated on a 24-hour-per-day schedule without disturbance to surrounding military operations. Cost data not included.
Chlorinated Solvent Contamination—Pilot Scale Studies/Demonstrations				
Soil	Drinking Water, Air	Passive Barrier Wall	Ch. III p. 92	Site 1—Canadian Forces Base, Borden, Ontario, Canada—Pilot Scale—Permeable reaction using an iron-based catalyst intercepted a VOC contaminated plume. This was a pilot test, to determine if the wall could degrade halogenated organic compounds. TCE 250 mg/L, PCE 43 mg/L reduced by 95% and 91% respectively. Cost data not included.
Soil	Water, Plant Life	Combination of soil washing and Fenton's reagent	Ch. III p. 92	Site 2—Arctic Regions in Canada—Combined Soil Washing and Fenton's Reagent for PCBs—Demonstration —Two groups have been looking at poly-chlorinated biphenyl (PCB) soil contamination on sites in the Canadian Arctic. The isolation, short summer season, and poor weather conditions make clean-up projects more difficult. The most promising non-destructive studies demonstrated were undertaken at two arctic sites, Resolution Island (Northwest Territories), and Saglek (LAB-2, Labrador). Preliminary bench-scale results indicated that the use of Fenton's reagent might be an effective method of treating PCB-impacted soils in the north. Therefore, a field project began in Saglek and Resolution Island with sample sizes of 10 to 40 kg of soil contaminated with PCBs. Three soil washings with water and/or hydrogen peroxide, then Fenton's agent, reduced PCBs by 75%, with 30% reduction due to soil washing and 45% due to Fenton's reagent. Cost data not included.

Table 1. (Continued)

Media	Threat	Restoration Technology(ies)	Chapter/ Page	Cases
Heavy Metal Contamination—Case Studies				
Soil & Groundwater	Drinking Water, Food	An impermeable cover, a cut-off wall to stop horizontal groundwater flow, and extraction and cleaning of ground water, prevention of crops from the area being eaten.	Ch. IV p. 98	<p>Site 1—Metallochemia Industrial Area, Budapest, Hungary—The factory, begun in 1910, sits on a 20-hectare site in southern Budapest. Activities included recovery of lead-containing materials, copper electrolysis and melting, black-copper technology, chrome alum manufacturing technology, technology of production of lead articles and copper alloys, and recovery of battery wastes. Protests of nearby residents in the mid-1980s led to soil- and groundwater-contamination studies. Based on the results, local health authority shut down the plant in 1990. About 200,000 m³ of soil and slag is contaminated with lead and zinc (80%), copper (14%), and tin (3%).</p> <p>Groundwater contaminants are zinc, cadmium, sulfides, phenols, and, to a smaller extent, lead. For the Metallochemia area, isolation is optimum remediation method, with an impermeable cover layer on the dump's surface, a cut-off wall around the area, fencing off horizontal groundwater flow in the water-bearing layer, and extraction and cleaning of groundwater within the isolated area. Near Metallochemia, and especially in the town of Nagytétény, removal of contaminated soil seems the best solution. Removed contaminated soil can put on the surface of dumpsite. Approximately 2.0 billion Hungarian Forint (US\$ 10 million) will be required, which is more than market value of factory site.</p>
Soil	Soil, Water	Physical processing to remove bullet fragments, physical and chemical processing to remove fine parts of lead and copper	Ch. IV p. 103	<p>Site 2—Sweden—Handling of Lead-Contaminated Soil and Scrap Metal from Small Arms Firing Ranges—Small-arms and open firing ranges in Sweden are being cleaned. After removing lead- and copper-contaminated soil to minimum depth (60 cm), soil is processed both physically and chemically. Three waste streams are pure lead from bullet fragments, which is recycled; lead slurry/sludge, which is properly disposed; and cleaned soil (cleaned to required standard or less), which is reused in firing range berms or in pavement. Costs from different firing ranges varied from 675-865 Swedish Krona (US\$ 78-100) per cubic meter.</p>
Soil	Water	Phytoremediation	Ch. IV p. 106	<p>Site 3—Former Canadian Forces Base Chilliwick—Phytoremediation Project—Two groups developed a multi-year strategy using phytoremediation to remediate 7,500 m³ of lead- and copper-contaminated soil from a 300-meter rifle range. In 1996, range soil was excavated and stockpiled on site. Sample analyses showed stockpiled soil to contain elevated levels of lead (average concentration: 943 ppm/maximum 3,700 ppm) and copper (average concentration: as 187 ppm/ maximum 740 ppm). In spring 1999, soil was relocated to a training area for phytoremediation project plots to be constructed over an impermeable geomembrane to prevent contaminant migration. The first field trial season was completed in 1999. Laboratory analyses and greenhouse experimentation results are not available as of this printing. Cost data not included.</p>

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II. FUEL HYDROCARBONS (LNAPLS)

Plumes of fuel hydrocarbons in the environment generally present low risk to life and health. Components of fuels that dissolve in water (soluble) are the most toxic to human beings and other living organisms, but these are also the components that are readily attenuated by physical, chemical, and biological means in a process called natural attenuation. Components of fuels that do not dissolve in water (insoluble) are of little or no risk to life and health.

Fuel hydrocarbon cleanup technologies are based on accelerating one or more of the physical, chemical, or biological components of natural attenuation. Field-ready cleanup technologies are well characterized for fuel contaminants such as aviation and vehicle fuels, diesel, kerosene, creosote, and some polyaromatic hydrocarbons. Technologies include soil venting or soil vapor extraction, bioventing, air sparging, separate phase recovery including bioslurping, and natural attenuation.

One of the main reasons for choosing a particular cleanup technology is cost, which is a consideration in Central and Eastern Europe. Of these field-ready technologies, bioventing and biosparging are the least costly. Although natural attenuation may seem to be least expensive, it costs about the same as bioventing and biosparging because of the monitoring required. Separate phase recovery is expensive because of pumping costs; soil venting is expensive because of having to deal with the fuel vapors.

Some of these technologies are showcased in this document as stand-alone treatments. Some technologies are included as part of a mixed-waste site remediation program, while others are not in this volume, but are described in Volume I.

A. CASE STUDIES

Soviet troops used 72 locations in the Czech Republic from 1968 to 1990. Contamination and damage was found at 60 of these locations. The overall amount of contaminated soil was estimated to be 1.24 million cubic meters (m³). Due to the need for massive groundwater pollution cleanup, immediate emergency cleanup pumping

started at 54 sites. Contaminants included LNAPLs, DNAPLs, poly-chlorinated biphenyls (PCB), heavy metals, and other toxic substances.

Decontamination and cleanup started in 1991 and, at present, only 9 localities are still being cleaned up. The former military area at Ralsko (an area of about 250–300 km²)¹, which includes the former air base at Hradčany (Site 2 below), was the largest area used by the former Soviet Western Troops Group (WTG). One thousand tons of LNAPLs have been removed from this area. In order to reach the acceptable cleanup levels, about 4000–5000 tons of LNAPLs must still be removed. The decontamination should be complete in 2008.

The former Soviet military area of Mladá (area about 60 km²) is described in Site 1 below. The military air base Boží Dar at Mladá is polluted mainly by LNAPLs. Decontamination is expected to be complete in 2005.

All investigation and remediation work was paid by Czech state budgets. From 1990 to 1998, government costs for site investigation, decontamination, risk analyses, and supervision were about CK 890 million (about US\$ 29.5 million).² Only the most necessary remediation projects were addressed. Additional costs are expected to be about CK 400–450 million (US\$ 15 million) from 1999 until the expected completion date in 2008. Total costs for decontamination of groundwater and soil and removal of dumps are now estimated around CK 1.3–1.4 billion (US\$ 50 million).

1. Site 1—Environmental Restoration at Milovice-tábor (Milovice Training Ground), Czech Republic³

Contaminants—Hydrocarbons (LNAPLs), chlorinated hydrocarbons (DNAPLs) (their value is below cleanup limits), and halon contamination reaches 30 meters deep in the unsaturated zone. Although data on location of the LNAPLs and DNAPLs were unavailable, such contaminants migrate to different locations and depths, depending on the density of each compound and the local geology.

Media—Parent rock, sandy limestone, silt, limestone, limy clay, and cretaceous sediments. Grain is larger with depth. In the deeper parent material, non-permeable lime desks (banks) exist, but tectonic lines and open fissures (rifts) are often very long. The

¹ The Czech Republic is approximately 80,000 km².

² At 1998 rates of exchange.

³ This site is included in the chlorinated solvents section also.

Mlynařice River Valley is surrounded by quaternary blow sediments (2–3 meters thick) and alluvial sediments 8–9 meters thick at average (sometimes 15–20 meters thick).

Coefficient of hydrological permeability is 10^{-4} – 10^{-5} , but there is good percolation through fissures. Groundwater level is 3 (the river Mlynařice basin) to 41 meters (large-scale oil storage) deep.

Threat—Contaminant poses threat to groundwater and local drinking water sources (wells). Migration into the Mlynařice River has been stopped by a hydrological shield.

Restoration Technology—Different strategies are used at different facilities:

- Large-Scale Oil Storage—Biodegradation *ex situ*, groundwater pumping with protective depression (8–10 liters/second of contaminated water has been pumped), venting.
- Siding and Manipulation Tanks (20 tanks, each holding, 20,000 liters) with Heavy Contamination—Biodegradation, surfactant usage, free phase pumping.
- Garages (Autoparks 1, 2, and 3)—Biodegradation, surfactant usage, free phase pumping, groundwater pumping (11 liters/second of contaminated water has been pumped), venting. Recycling of the asphalt surface areas and roads. Removal of buildings and washing bridges.
- South Gate—Hydraulic barrier at the Mlynařice River, demolition of building, biodegradation *ex situ*, groundwater pumping (5–10 liters/second of contaminated water has been pumped). Halons will be pumped out of the pipes remaining after computer central installation.

Location—Central Bohemia, 30 km north of Prague, this site is a part of the former Soviet military area of Mladá (area ca 58 km²) on the south border (Milovice Training Ground or Milovice town).

Description—The size of the city area is about 4 km². Five contaminated sites are mentioned: oil storage (LNAPLs, DNAPLs), three garages (LNAPLs), and a building near the south gate (DNAPLs in the former clothes-cleaning building and halons in the computer center building)

History—This area has been a military base since the time of the Austrian Empire. It was also used for military purposes after the Czechoslovak Republic was established in 1918 and during the German occupation until 1945. After WWII the Army of the Czechoslovak Republic used it again. From 1968 to 1992, the Soviet Union

occupied it. Some of the contamination has been here since the Austrian Empire, while some massive contamination occurred in World War II. Investigation and cleanup started in 1989 (two companies carried out most of the work: Aquatest Prague until spring 1996, then Top Eko Příbram from 1996 to 1998). From April 1997 to August 1998, only monitoring was needed, and since September 1998, a groundwater protection company, OPV Ltd., has been working there. OPV intends to finish the cleaning up of the entire camp in 2005 and then to continue with monitoring for 2 more years. About 2000 cubic meters (m^3) of soil have been excavated. The hydrocarbon contamination varies from 100 mg/kg soil to 10,000 mg/kg soil (maximum concentration of contaminants reaches 38,000 mg/kg of dry soil).

The total amount of contamination is not recorded. Specifics about success of treatment and post-treatment levels of contamination were not included with this case study.

Cleanup Standard Limits—LNAPLs: 1500 mg non-extractable substances (NES)/kg of dry soil and 5 mg/liter; DNAPLs: 120 micrograms (μg)/liter of groundwater and 20 $\mu\text{g}/\text{m}^3$ in soil air.

Costs

- August 1998 to 2007: CK 86 million (US\$ 2.7 million), for the OPV Company only
- May 1997 to August 1998: Monitoring only: CK 13 million (US\$ 410,100)
- April 1996 to May 1997: CK 35 million (US\$ 1.1 million) (Top Eko Příbram totals CK 47.94 million)

Cleanup from 1994 to 1996 (Aquatest budget):

- 1996: CK 2 million (US\$ 74,074)
- 1995: CK 30 million (US\$ 1.13 million)
- 1994: CK 6 million (US\$ 208,333)
- Years prior to 1994: approximately CK 0.8–1.5 million per year.

Remarks

1. Be alert to the exchange rate of Czech Koruna (CK) to US Dollars (US\$), and be aware of inflation. The CK has experienced dramatic price inflation from 1994-1999.
2. The Ministry of Environment paid for these locations where investigation and restoration began, but no comprehensive data are available.

2. Site 2—Former Air Base Hradčany, Czech Republic⁴

Contaminants—LNAPLs, DNAPLs

Media—Saturated zone, non-saturated zone.

Threats—To the Ploučnice River and sources of underground drinking water.

Restoration Technology—Cleanup pumping, venting, bioventing, air sparging.

Location—The village of Ralsko in the north of Bohemia (approximately 80 km from Prague) and near the German border at Zittan.

Description—Former military air base with POL supply infrastructure (tanks, pipes, siding, pumps, hydrants, and delivery points), workshops, army barracks, and accommodation for soldiers and families.

History of the Site—It was a former military area of the Czech Armed Forces and of the Former Soviet Union from 1968 to 1992.

Area of Contamination—Area ranging to hundreds of hectares.

A Specific Case at Air Base Hradčany—*In-situ* remediation of soil and groundwater polluted by jet fuel on the former Air Base Hradčany, Czech Republic.

Site Characteristics—The former Hradčany military air base is located in Northern Bohemia, near the district town Ceska Lipa. Nazi Germany built the air base in 1944; it was used by the Soviets from 1968 to 1990. The air base and its vicinity are in the sedimentary complex of the Bohemian Cretaceous Basin, which forms the main groundwater supply of the Czech Republic. Pollution of soil and groundwater by jet fuel is spread in the alluvial sediments of Ploučnice River and in the Middle Turonian sandstones.

The Middle Turonian unconfined aquifer reaches an average thickness of 70 meters. The aquifer permeability is of the fissure-porous type, hydraulic conductivity averages at 8 meters/day, reaching up to 30 meters/day in the upper part of the aquifer. Groundwater level is 4–6 meters below the surface in the polluted areas. Annual groundwater level fluctuation varies between 0.3–0.7 in the area of interest.

Groundwater of the Middle Turonian aquifer flows through the contaminated area of the air base towards the Ploučnice River. Water quality is endangered by seepage of groundwater polluted by oil hydrocarbons. A water works (with capacity 35

⁴ This site is included in the chlorinated solvents section also.

liters/second), drawing from the Middle Turonian aquifer, is located near the air base. The wellhead protection area partly overlaps the area of groundwater pollution based on the results of groundwater modeling. The pumped amount was reduced to prevent the polluted water from entering the well field area.

Soil and Groundwater Pollution—According to the results of gas chromatography/mass spectrometry (GC/MS) analysis, the pollutants were jet fuel, 66.0 percent; diesel oil, 19.5 percent; petrol, 8.0 percent; fuel oil, 6.0 percent; and chlorinated solvents, 0.5 percent.

Operational leakage during the past 40-year period has resulted in mixed contamination concentrated in soil around groundwater level fluctuation. The smear zone averages 1.2 meters below the current groundwater level. The total contaminated thickness with the smear zone averaged 1.7 meters.

The entire soil profile is contaminated in storage areas, where tanks with jet fuel were stored on sandy soils without any protection. The thickness of free oil product at the very beginning of remediation in 1989 reached maximum 6 meters, and the median or common thickness varied from 5 to 80 cm in storage areas.

The heavily polluted area of soil and groundwater (exceeding cleanup limits) covers about 17 hectares. The volume of contaminated soil was estimated at 290,000 m³, while the total quantity of oil hydrocarbons in soil was estimated at 5400 tons.

The cleanup limits given by the Czech Ministry of Environment, based on the results of risk analysis, were as follows:

- Oil hydrocarbons in soil = 5000 mg/kg
- Oil hydrocarbons in groundwater = 5 mg/L
- BTEX in groundwater = 1000 µg/L
- Chlorinated solvents = 1000 µg/L.

Remediation—Remediation started in 1989. The most heavily polluted areas had between 24 and 32 boreholes placed in them. Water was pumped, then treated in gravitational separators and finally in a sewage water treatment plant. This two-step treatment approach enabled the pumping of relatively large amounts of groundwater (25 liters/second), as well as meeting the cleanup standards of oil hydrocarbon content (0.5 mg/liter) before return to the river.

In 1993, a bioventing method was implemented over a 3.5-hectare area. This bioventing field operated successfully over a 3-year period. Venting wells were located

in regularly spaced networks either 10 x 10 meters or 15 x 15 meters in accordance with the results of soil gas permeability tests.

When the pump-and-treat method decreased in efficiency in 1996, a dual-phase extraction was implemented. This method enabled suction of free phase from venting wells, which were equipped with a screen 2 meters below the groundwater level.

Controlled aerobic bioremediation efforts started in 1996. A bacteriological screening of soil and groundwater found that relatively high densities of soil bacteria were present in polluted areas that degraded the fuels. Laboratory tests indicated that more rapid bacterial growth would occur if nutrients were added (nitrogen, phosphorus, potassium). Growth was 5–10 times more in comparison to control samples. The proper composition of nutrients was then tested in the laboratory. In the field, respiration tests and venting monitoring determined the proper composition of nutrients in the bioventing fields.

A crucial condition for aerobic biodegradation is a sufficient supply of oxygen. Two systems are used for oxygen delivery: venting and air sparging, using ambient air to bring in oxygen. The venting method could not address the most polluted part of soil profile around the smear zone (the water table fluctuation). For this reason, air sparging was implemented to promote bacterial activity.

In 1996, air-sparging wells were drilled in networks of 15 x 15 meters. The height of the water column was determined to be 6 meters. The increased concentration of oxygen in groundwater was measured and was considered the most important effect of air sparging.

Agricultural fertilizers were added through the venting pipes. Nutrient addition showed positive results after 6 months. The distribution of fertilizers in groundwater was very irregular in the first year. After the second year of application, the distribution of concentration of fertilizer was more even, and biodegradation rates increased. During the first year of controlled bioremediation (venting + air sparging + nutrient addition), the average biodegradation rate reached 2 mg/kg/day. During the second year, the average biodegradation rate was 5 mg/kg/day. Biodegradation activity was monitored by measurements of concentrations of respiration gases in the venting system (for total biodegraded amount) and by conducting *in situ* respiration tests using respiration probes at specific points.

In 1999, a controlled bioremediation was implemented in a 10-hectare area and bioventing and dual phase extraction on 5.1 hectares. The total remediated area was 15.1

hectares, with 950 bioventing wells (25 blowers, each at 180 m³/hour), 650 air-sparging wells (8 compressors, each at 100 m³/hour), and 180 dual suction wells (9 vacuum pumps, each at 80 m³/hour). Groundwater was pumped from 12 wells with total discharge 4.5 liters/second. This effort was ongoing through the end of 1999.

Remediation Results—The pump and treat method was relatively successful over a long period (1989–1996), due to the large amount of free product. After a time, however, the output of oil hydrocarbons from pumping wells decreased, so dual phase pumping on bioventing fields was implemented (see Table 1 below). After 1997, controlled bioremediation has become the most successful method of remediation, promising results that can meet the relatively high cleanup limits.

The cleanup of the Hradčany airport is planned to continue through 2008. Areas where the oil pollution exceeded cleanup limits are divided into remediation fields (0.5–4 hectares each). Remediation of a field is projected to last approximately 6 years. Monitoring of residual pollution will start once cleanup limits are achieved.

Table 1. Results of the Groundwater and Soil Cleanup on the Hradčany Airport (1989-1999)

Units are in metric tons (1 ton = 1000 kg) of mixture of fuels or oil hydrocarbons

Methods	Years								Total
	1989–1992	1993	1994	1995	1996	1997	1998	1999	
Water Pumping ^a	238	23	52	79	45	52	35	31	555
Venting		2	7	36	34	7	32	11	129
Bioremediation			18	43	86	109	131	191	578
Grand Total	238	25	77	158	165	168	198	233	1262

^a Dual phase extraction is included in water pumping balance from 1996.

The Czech Ministry of Environment funded the remediation. The final stage of remediation is planned for the period from 1997 to 2008. The total planned costs of proposed remediation are CK 344 million.

3. Site 3—Milovice Air Base Boží Dar, Czech Republic⁵

Contaminant—LNAPLs (jet fuel, diesel, engine oil), DNAPLs (trichloroethene, tetrachloroethene).

Media—Saturated zone, non-saturated zone.

⁵ This site is included in the chlorinated solvents section also.

Geology—This is the Bohemian Cretaceous Basin, with sandy limestone and siltstones with deep weathering about 3–4 meters (sandy clay soils), and residual quaternary terrace sediments (sandy gravel soils) some meters thick.

Hydrogeology—The groundwater level of the first Cretaceous aquifer is 5–8 meters deep. The groundwater flow is generally south, but the local groundwater flow varies depending on permeable fractures.

Threat—To sources of drinking groundwater, especially individual groundwater wells in the nearby village of Zbozicko, and to surface water. Nearby creeks of Vlkava (to the east) and Mlýnařice, on the southern edge of the air base, are threatened.

Restoration Technology—Removal of buildings, pump and treat, venting, and biodegradation. Thousands of cubic meters of contaminated soils were remediated by biodegradation. Hundreds of thousands of cubic meters of contaminated groundwater were pumped out beginning in 1991. Several hundred tons of LNAPLs and several hundred kilograms of chlorinated hydrocarbons have been removed.

Location—Central Bohemia, 30 km north of Prague, part of former Soviet military area of Mladá (area about 58 km²) at the south border (Milovice Training Ground or Milovice town).

Description—Former military air base with POL supply infrastructure (tanks, pipes, and pipeline), garages, workshops, stores, chemical cleaning facilities, army barracks, accommodation for soldiers and families.

Area of Contamination—About 10 percent of the whole area, which is about 10 km², was contaminated to a depth about 20 meters.

History of Site—This area was a military base since the time of the Austrian Empire. It was used for military purposes after the Czechoslovak Republic was established in 1918 and during the German occupation. After the German occupation, it was used again by the army of the Czechoslovak Republic to 1968, and by the Soviet Union from 1968 to 1992.

4. Site 4—Olomouc—Neředín, Czech Republic⁶

Contaminant—LNAPLs, DNAPLs

Media—Saturated zone, non-saturated zone

Threat—To local sources of underground drinking water (private wells)

Restoration Technology—Removing of buildings, cleanup pumping, venting.

Location—Olomouc city in central Moravia (about 240 km east of Prague).

Description—Former military helicopter base with workshop and maintenance, garage, army barracks, and POL facility.

Area of Contamination—Hundreds of hectares.

History of Site—Former military army barracks used from 1968 until 1992 by Western Troops Group.

Cleanup Standard Limits—Not included.

Costs—Not included.

5. Site 5—Zákupy, Czech Republic

Contaminant—LNAPLs (light petroleum and aromatic hydrocarbons)

Media—Saturated zone, non-saturated zone.

Geology—Bohemian Cretaceous Basin, Turonian thick-bedded sandstones, with deep weathering about 2 meters of sands: fluvial bed sorted sediments around the Svitávka creek about 6 meters thick (gravel-sand-silt-clay sediments in a wide marshy flood plain).

Hydrogeology—The groundwater level of the first Cretaceous aquifer is 2–4 meters below the surface. The groundwater flow is in the direction of the Svitávka creek, about 50 meters west. Permeability is mostly in pores near the surface, and partly in fractures below the surface.

Threat—To collectors of drinking water with regional sources and the brook Svitávka.

Restoration Technology—*Ex situ* biodegradation, venting, cleanup pumping.

⁶ This site is included in the chlorinated solvents section also.

Location—The village of Nové Zákupy, near Kuřivody.

Description—Former POL storage in the sandstone quarry.

Area of Contamination—About 1 hectare.

History of Site—POL storage was started by the Soviets in the 1970s.

Cleanup Standard Limits—Not included.

Costs—Not included.

6. Site 6—Jirice (in the District of Mladá Boleslav) Central Bohemia⁷

Location—The Jirice site is situated to the north of Prague on the left bank of the Jizera River near the towns of Benátky and Jizerou.

Contaminant—The presence of underground oil is connected with the handling and storage of liquid fuels. Hot spots of groundwater and vadose zone contamination with chlorinated hydrocarbons exist, probably resulting from dumping of used chlorinated solvents. The source of local high zinc concentrations in the groundwater may be from the use of ammunition on the nearby firing range.

Chlorinated aliphatic hydrocarbons [trichloroethylene (TCE), perchloroethylene (PCE)] were the main contaminants at this site, exceeding general Czech limits “C” for CHC in groundwater (e.g., TCE 50 µg/L, PCE 10 µg/L). They were accompanied with oil hydrocarbons and aromatics in lower concentrations in groundwater, but in significant concentrations in soil air as well.

Contamination of groundwater with zinc exceeding limit “C” (5 mg/L) was also observed (maximum 2200 mg Zn/L) but only in a few wells. This zinc contamination had no causal connection with oil hydrocarbons and/or chlorinated hydrocarbons in the aquifer.

Media—From a geological point-of-view, the subsurface is predominantly fractured, with tectonic faults and crevices that also affect groundwater flow and contaminant migration. The groundwater table lies between 20–35 meters below ground level. The site is situated in the vicinity of a hydrogeological water shed divide.

Threat—The hydraulic gradient declines to the Jizera River valley where wells of the regional Káraný waterworks are situated. The distance between these wells and the

⁷ This site is included in the chlorinated solvents section also.

Threat—The hydraulic gradient declines to the Jizera River valley where wells of the regional Káraný waterworks are situated. The distance between these wells and the contaminated area is about 3 km. The Jirice site lies within an outer protective zone of the Jizera River.

History of Site—It was a part of a vast military training area called Mladá that was occupied by the Soviet Army in August 1968. This area was not inspected until 1990, when discussions about the Soviet troop withdrawal began. (Comment from the contributor of this case study: “The following data on land use may not be reliable.”) Contamination was greatest at the so-called Camp No. 19 (800 x 900 meters), where there was a parking lot for trucks and combat vehicles, workshops, and fuel storage with 20 underground tanks for diesel and petrol with a total volume of 1240 m³. A mobile laundry also may have been present. A large firing range (750 x 500 meters) was situated close to Camp No. 19.

Restoration Technology—The decrease of chlorinated hydrocarbon concentrations in cleanup wells during remediation of groundwater is shown in Table 2. The following local limits were set for groundwater: benzene, 10 µg/L; toluene, 1000 µg/L; PCE, 10 µg/L; total CHC, 30 µg/L. These limits changed when it was decided that the area under remediation would be used as an industrial zone with the existing drinking water supply from the external municipal waterworks. The on-site limits of chlorinated hydrocarbons then were made in accordance with the calculated off-site risks as follows: PCE, 100 µg/L; total CHC, 300 µg/L.

Table 2. Average Concentration of Chlorinated Hydrocarbons in Groundwater at Jirice Site

Remediation Well	Chlorinated Hydrocarbons in µg/L					
	1993	1994	1995	1996	1997	1998
HJ 2	441	482	387	177	89	84
HV 11	172	225	99	36	9	7
HV 12	158	207	137	97	66	73
HV 15	246	206	155	9	16	23

Soil gas in the deeper part of the unsaturated zone (5–30 meters) at the very beginning of cleanup contained hundreds of mg/m³ of oil hydrocarbons (up to 760 mg/m³), high concentrations of aromatics, mostly toluene (up to 478 mg/m³) and tens to hundreds of mg/m³ of chlorinated hydrocarbons (up to 390 mg/m³), mostly PCE followed by TCE. Daughter products such as dichloroethane, dichloroethylene, tetrachloromethane, and chloroform were found at much lower concentrations.

The following local limits for soil air were set for the depth of 1 meter below ground: toluene, 70 mg/m³; and total CHC, 6.5 mg/m³. During remediation, oil hydrocarbons disappeared completely and the content of chlorinated hydrocarbons was at least halved; 75 percent of the venting boreholes became practically clean. (The process yielding this result was not included in this case study.) Only one well contained high concentrations of CHC (100 mg/m³ at the maximum) and this occurred in the deep part of the unsaturated zone. The shallow part of unsaturated zone (0–2 meters) contained concentrations one order of magnitude smaller both for HC and CHC vapors at the beginning of soil vapor extraction (SVE), and at the end of remediation the concentrations of oil and chlorinated hydrocarbons declined to near zero.

Remediation of groundwater was based on pumping and treating from 5 to 8 wells. There were three aims of pumping: to create protective hydraulic depressions; to remove the contaminants from the aquifer; and to extend the thickness of the unsaturated zone in the vicinity of the capillary fringe for the intensification of the SVE. The total yield of pumped water varied from 5 to 12 liters/second depending on the climatic conditions. The remediation started in 1993 and was finished in 1998. Pumped water was treated by air stripping in three towers. To enlarge the water/air interface, the tower was filled with loose plastic fillings. After stripping, the air was cleaned through activated carbon filters that were recharged on-site with the help of steam. Condensed chlorinated solvents were burned off-site. The cleaned water was recharged totally on the outskirts of the contaminated plume either via sprinklers on the ground surface or by injection into infiltration wells. In the second case, water was treated on the two stripping towers in series. During remediation, 2 kg of oil hydrocarbons and 249 kg of chlorinated hydrocarbons (mostly PCE and TCE) were removed. Water containing high concentrations of zinc was pre-treated with the help of a zeolite filter.

Remediation of the unsaturated zone was based on SVE, air injection, and its intensification by well blasting. There were two venting fields consisting of 5 extraction wells, each finished above groundwater level at depths of 15–30 meters. Four deep wells for remedial pumping (with depth to 40 meters) were situated at the point of massive contamination and the conducting fractures throughout the site. These four wells were later incorporated into the SVE system.

The SVE system consisted of three vacuum pumps (capacity of 60 liters/second) and one vacuum pump (capacity of 30 liters/second). One pressure blower (capacity of 50 liters/second) was used for air injection into relatively clean wells on the outskirts of the contaminated area to accelerate decontamination processes. The vapor treatment

system consisted of a dehumidifier unit and active carbon filters; during hot weather, this included a cooler. The SVE system operated from February 1995 to December 1998. Extraction wells were switched on and off according to the actual level of CHC concentrations. The respective system was shut off when CHC concentrations declined repeatedly below standards (individual CHC 10 mg/m³), or when the removal rate was lower than 5 kg of volatile contaminant per month. The exception was one permanently contaminated well where remediation was ended when the local limits were reached for groundwater and the uppermost part of unsaturated zone.

When a very low contaminant flux occurred, well blasting was successively employed as shown in Table 3.

Table 3. Effect of Well Blasting on Hydrocarbon Concentrations in Soil Air During Experimental Soil Vapor Extraction (12 liters/second) at Jirice Site

Well	Under Pressure Caused by SVE Before Blasting (kPa)	HC Content in Soil Air Before Blasting (mg/m ³)	Under Pressure Caused by SVE After Blasting (kPa)	HC Content in Soil Air After Blasting (mg/m ³)
Ji 1703	6.2	0.0	3.2	220
V 1709	14.5	0.0	1.2	350
V 1714	14.0	0.0	4.2	60
V 1717	14.5	350.0	8.0	1000
V 1712	12.5	220.0	9.0	3600

kPa = kilopascal

Soil vapor extraction removed 285 kg of oil hydrocarbons and 1610 kg of chlorinated aliphatic hydrocarbons. Another 5000–10,000 kg of oil hydrocarbons were estimated to be decomposed by microbial activity during SVE and air injection, according to a rise of CO₂ content in the exhausted soil air and its comparison with the soil air in clean parts of the unsaturated zone.

Cost—The total cost of groundwater remediation, including quality monitoring, was CK 9.2 million (US\$ 2.7 million). The total cost of soil vapor extraction was CK 4,669 million (US\$ 154,600).

Documentation

1. Svoma, J., *Cleanup of Jirice Site and Emergency Self-guarding Pumping at the Mladá Military Base Between Jirice and Vsejany Sites: Final Report*, M. S. Aquatest SG Praha, Ministry of Environment Praha, Czech Republic, May 1999. (In Czech)
2. Svoma, J., Kroova, H., *Experience with Remediation Investigation and Research of Contaminated Sites in the Czech Republic*. "Draft for Tour de

Table" Presentation for Phase III NATO/CCMSD Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment and Cleanup of Contaminated Land and Groundwater. Held at the Hotel Bleu Marine, Angers, France, 9-14 May 1999.

7. Site 7—Hvezdov, Northern Bohemia⁸

Contaminants—LNAPLs (hydrocarbons: petrol, diesel oil, engine oil, heating oil), DNAPLs (tetrachloromethane).

Contaminant Sources—LNAPLs came from motor pools, vehicle repair sites, oil storage, boiler houses, and coal stocks (dangerous liquid pollutants were poured out into coal stocks and then burned up—unfortunately a significant part of the pollutants infiltrated into subsoil), oil transformers, and petrol stations. The DNAPLs emanated from the extinguishing medium in military rocket launchers.

Media—Soil and subsoil.

Geology—Bohemian Cretaceous Basin, Turonian thick-bedded sandstones, deep weathering of about 6 meters creating sandy soils, 4- to 6-meter-thick fluvial bed sorted sediments around small creeks with gravel-sand-silt-clay sediments.

Hydrogeology—The groundwater level of the first Cretaceous aquifer is 4–10 meters. The groundwater flow is in the direction of local creeks.

Threat—The threat to a very important regional aquifer used for drinking water and a significant waterworks. The Plouznicky Potok creek is a stream used as drinking water, but its drainage basin includes contaminated groundwater. The original water wells that supplied Hvezdov were threatened too, but because people did not live in Hvezdov in the 1990s, that water supply was not used. A new water supply for new settlers now comes from the nearby town of Mimon.

Restoration Technology—*Unsaturated zone*. Soils with LNAPL concentrations over cleanup limits were removed from the site and biodegraded in special biodegradation fields.

Soil vapor extraction methods removed significant amounts of volatile aromatic and chlorinated hydrocarbons from contaminated soils.

⁸ This site is included in the chlorinated solvents section also.

Saturated zone. Groundwater pumping, followed by stripping and filtration, intercepted the contaminant plume. There were two main pumping centers: Hvezdov I, pumping about 3–5 liters/second of contaminated water with only LNAPLs, and Hvezdov II, pumping about 10 liters/second of both LNAPLs and DNAPLs. The groundwater pumping had functioned as a hydraulic barrier to help protect the water quality in creeks.

Location—The site Hvezdov is in northern Bohemia, about 80 km from Prague, near the town of Mimon, between other Soviet military sites (Hradčany 2 km, and Zákupy 8 km). The site has an area of about 15 km².

Description—This site was a former Soviet military rocket base from 1968 to 1990. Before Soviet occupation, it was an agricultural and forest area.

Amount of Contamination—About 4 percent of the area was contaminated to a depth of about 20 meters. Approximately 10,000 m³ of contaminated soils were remediated by biodegradation methods. About 500,000 m³ of contaminated groundwater was pumped out between 1991-1995, when the remediation was completed. Approximately 400 kg of trichloromethane were removed, and about 50 tons of LNAPLs. The residual concentrations at the completion of remediation were: soils, 1000 mg/kg of LNAPLs; groundwater, 5 mg/L LNAPLs; groundwater, 100 µg/L of trichloroethane.

Costs

- 1990-1991: Site investigation: CK 3.7 million (US\$ 125,000), total cost.
- 1991-1995: About CK 25.9 million (US\$ 977,000) total.
- The original budget for remediation was estimated to be larger, and strict cleanup levels were set (analogous to drinking water quality) but not reached. Because of the lack of money in the state budget, remediation efforts were completed in 1995, though originally planned to run to 1997. Most contaminants were removed or remediated.

8. Site 8—Lustenice, Central Bohemia⁹

Contaminants—LNAPLs (hydrocarbons: petrol, diesel oil, engine oil, heating oil), DNAPLs [tetrachloroethene (perchloroethene, PCE) and trichloroethene, TCE].

Contaminant Sources—LNAPLs from motor pools, vehicle repair sites, oil storage, oil transformers, petrol stations; DNAPLs from chemical cleaning and laundry facility.

⁹ This site is included in chlorinated solvents also.

Media—Soil and groundwater.

Geology—Bohemian Cretaceous Basin, Turonian marlites, sandy marlites, siltstones, with deep weathering about 3–4 meters (sandy clay soils), and fluvial bed sorted sediments 2–3 meters thick around the Struzsky Potok creek (gravel-sand-silt-clay alluvial sediments).

Hydrogeology—The groundwater level of the first Cretaceous aquifer varies from 3–20 meters below the surface. The groundwater flow is in the general direction of the Jizera River (about 2 km to SW), but the local groundwater flows vary due to permeable fractures in the subsurface.

Threat—Groundwater flows into the Jizera River. Surface water and groundwater pumped from the Jizera River fluvial sediments (including artificial recharge facilities) are used as drinking water for Prague. The waterworks of Káraný have a capacity of 120 liters/second.

The original Soviet water wells for a former water supply in Lustenice were threatened, but people did not live there in the 1990s. A new water supply for new settlers comes from the nearby waterworks of Káraný. The Struzsky Potok creek was heavily contaminated by LNAPLs and DNAPLs (both surface water and stream sediments), which supplied individual wells in the nearby village of Struhý, about 1 km away.

Restoration Technology—*Unsaturated zone.* Soils with LNAPLs over cleanup limits were removed from the environment and biodegraded on site in special biodegradation fields. Soils with a significant amount of both aromatic and chlorinated volatiles around the former laundry area were remediated by soil vapor extraction.

Saturated zone. Groundwater pumping was used in the contaminant plume in four places. First, the chemical laundry, which pumped about 3–5 liters/second of contaminated water (LNAPLs and DNAPLs); second and third, two military auto parks together pumped about 2–3 liters/second (LNAPLs); and fourth, a transmitter center, which pumps about 1 liter/second (heating oils). Filtration decontaminated the water at all four locations. The laundry area water was also air stripped and groundwater pumping created a radial hydraulic barrier to help protect the water quality in the civilian neighborhood.

Location—Lustenice is near the towns of Benátky and Jizerou in central Bohemia, about 30 km north of Prague, and near other former Soviet military sites (Milovice, Jirice and Boží Dar, all to the south). The site is about 17 km² in area.

Description—This site was a longtime military base: Austrian (before 1918), Czech (1918–1939), German (1939–1945), Czech again (1945–1968), and Soviet (1968–1990). As of 1991, the area is non-military. An industrial zone is planned here and much of the surrounding area will remain as forests.

Amount of Contamination—About 20 percent, or 3.5 km², of the 17 km² total area was contaminated to a depth about 30 meters. Approximately 10,000 m³ of contaminated soils were remediated by biodegradation methods. About 1,200,000 m³ of contaminated groundwater was pumped out from 1991–1995, when the remediation was completed. About 5 tons of chlorinated hydrocarbons and 100 tons LNAPLs were removed. The residual concentrations after completion of remediation were: soils, 500 mg/kg LNAPLs; groundwater, 5 mg/L LNAPLs; groundwater, 100 µg/L DNAPLs.

Costs

- 1990-1991 (site survey stage): US\$ 300,000
- 1991-1995: About US\$ 1,400,000

The original budget for remediation was estimated to be larger, and strict cleanup levels were set (analogous to drinking water quality) but not reached. Because of the lack of money in the state budget, remediation efforts ended in 1995. Most contaminants were removed from the site.

9. Site 9—Tököl Air Base, Near Budapest, Hungary

Tököl air base is located on the northwestern side of Csepel Island, 25 kilometers south of Budapest, Hungary. The Soviets used the air base from 1956 to 1991.

The environmental assessment discovered substantial hydrocarbon by-product pollution around the fuel storage tanks in 1991. The contamination was in the hydrogeological protective zone of the Halásztelek well field, which supplies Budapest with 60,000 m³ of potable water/year. An environmental assessment first estimated the hydrocarbon by-product contamination, and then a remediation plan was prepared.

Hydrogeological Structure—A clay layer is below the surface at a depth of 15–20 meters. Above it are sand and sandy gravel layers from the Holocene-Pleistocene age. The thickness of these layers is 10–15 meters. Holocene age sand and sandy silt is 2–5

meters thick on the surface. Permeability of the sandy gravel is 10^{-3} meters/second, while the sand and silty sand is characterized by 10^{-4} – 10^{-5} meters/second values.

The prevailing groundwater level is determined by three factors: the nearby Danube, precipitation, and the yield of the Halásztelek well field. The groundwater level is 4–5 meters below the surface. The groundwater seepage velocity is 40–60 meters/year.

Halásztelek well field is located 500–600 meters from the middle and northern part of the air base. According to the calculations, groundwater with 100–200 µg/liter total hydrocarbon concentration would have reached the Halásztelek well field if remediation had not been implemented.

Site Investigations—As a part of the assessment, a monitoring well system was installed to investigate the hydrogeological structure. Operators used the well system to take samples from the soil and groundwater, to test for hydrocarbon by-products, and to monitor the effect of the remediation activity.

As part of the fieldwork, 133 monitoring wells were drilled to a depth of 8–10 meters. Soil samples were taken at each meter of depth. Liquid samples (groundwater, hydrocarbon by-products) were taken from the monitoring wells every 3 months throughout a period of 2 years and twice a year after that.

The groundwater level was measured twice a week and, after a year, twice a month. The permeability of the ground was measured by pumping and infiltration tests. Recovery conditions were determined by pumping large diameter (160–400 mm) wells. Some of these wells were used during the cleanup as recovery wells.

Bail down tests and recharge test results measured the thickness of the free phase. Residual parts of the hydrocarbon by-products on the surface of the soil were tested in a laboratory. Samples from groundwater were tested to detect all dissolved hydrocarbons and dissolved aromatic and aliphatic hydrocarbon compounds.

Remediation Approach—Approximately 2200 m³ of jet fuel contaminated the ground and groundwater at Tököl air base. The aim of the first stage of remediation was to stop free-phase chlorinated hydrocarbons (CH) and dissolved hydrocarbons from spreading in the groundwater. To achieve this aim, both free-phase CH and dissolved phase CH were pumped out. The target concentration limit of dissolved hydrocarbons in the groundwater was 100 µg/liter total CH, while the target concentration limit in the soil was 100 mg/kg total residual CH. Remediation then proceeded through the following steps:

1. Water and free product were pumped from approximately five large-diameter (300 mm) recovery wells. The water table level was depressed significantly to speed up flow of product to the wells.
2. Air stripping of dissolved jet fuel components in the removed groundwater was done by forcing the water (1750 m³/day) through injectors and circulating the air with fans. The goal for the stripping was 100 µg /liter total hydrocarbons. (Air emission standards ranging from 2 grams/hectare for benzene to 200 grams/hectare for xylene were also to be met.)
3. Treated groundwater was recycled into a total of 35 injection wells.
4. The excess treated groundwater (400 to 500 m³/day) was pumped into the Danube via a jet fuel pipeline formerly used to pipe jet fuel from ships to the storage tanks of the air base.
5. To recover the free phase CH, a small-diameter filter scavenger pump was used in conjunction with a Grundfos-type water-table depression pump. The filter scavenger pump works on the principle of a semi-permeable membrane.
6. Part of the free phase CH was pumped from the wells by shallow well product system with selective oil skimmer. Clean Environment Engineers Inc. (CEE), in the United States, developed this system.

Remediation Results—The first stage of the remediation operation started on 10 December 1992 and lasted until 30 June 1993. During this period of time, 1980 m³ of free phase jet fuel and 1.8 million m³ of water contaminated with dissolved CH were recovered from the ground.

Cost Data—The cost of the project was Hungarian Forint 200 million (US\$ 1.0 million).

10. Site 10—Canadian Forces Base Borden, Ontario, Canada

The remediation of a former gas bar at CFB Borden, Ontario, is an excellent example of a successful biocell treatment application. Hydrocarbons (petrol) resulting from leaking underground storage tanks (removed in 1995) were found in the form of free product at the site. Because of large seasonal variations in groundwater levels, this free product stained the soil below the groundwater table (i.e., large smear zones). Hence, the groundwater was also found to be heavily impacted and thus required treatment (petrol is slightly miscible with water).

The first priority was to remove the contaminant source completely, because the potential existed for contaminants to migrate past property boundary lines. Upon

consultation, it was recognized that the construction of a biocell would allow for source removal as well as economical treatment of impacted soil.

The 2.5-meter-thick layer of hydrocarbon-impacted soil was located underneath 3.0 meters of clean soil. The overburden, or clean soil, was excavated and stockpiled for re-use. A groundwater pump-and-treat system was installed at the perimeter of the area planned for excavation to temporarily depress the water table in the excavation zone. The contaminated soil was then excavated and stockpiled in a separate area contained by liners. Free product was removed during excavation and the associated impacted groundwater was recovered and treated using a sand filter and activated carbon adsorption system before being discharged to a storm drain. Outside the biocell, Oxygen Releasing Compounds (ORCs) were added to the groundwater to enhance natural attenuation of the dissolved phase plume. The clean soil was backfilled first, in order to raise the depth of the pit above the normal groundwater elevation, and the base of the cell was graded properly to enable leachate collection. The base of the pit was then covered with a plastic liner/geomembrane on which the impacted soil was placed.

The leachate collection system consisted of sump pumps located in the lowest areas of the biocell. A layer of clean gravel was placed over the liner to facilitate drainage to the sumps. The impacted soil was then replaced, and water and nutrients were added to promote microbial activity. A SVE system was also installed near the bottom of the biocell to help volatilize the petrol components and to draw oxygen into the soil to stimulate microbial activity. The SVE's off-gases were treated on-site using a catalytic oxidizer. During operation, the leachate collected in the sumps was recirculated and distributed on the top of the biocell, ensuring proper moisture content for biodegradation and treatment of the contaminated soil and leachate.

Soil remediation was completed in 1997 and the remediation of the dissolved phase groundwater plume is progressing successfully. The initial site conditions reported TPH and BTEX component concentrations in excess of 14,000 ppm and 1000 ppm respectively for soil. After approximately 7 months of operation, soil analytical testing gave results not only well below the Provincial Environment Ministry's guidelines for industrial sites but, in most cases, below detection level. There also have been positive indications that the natural attenuation program involving ORCs has been successful in impeding and remediating the dissolved phase contaminant plume. Additionally, it was reported that the catalytic oxidizer had treated the equivalent of 1100 liters of petrol in the process of operation. The site was decommissioned in September 1999.

Cost Data—Not included.

11. Site 11—Synchronous Biological and Physical Techniques at Canadian Forces Base, Petawawa, Canada

Hydrocarbon contamination resulting from leaking underground storage tanks was discovered beneath the site of a gas bar in operation at CFB Petawawa. Computer modeling of the site revealed that the tanks were leaking as early as the 1970s. Delineation of the contaminated zone revealed that there was in excess of 6000 liters of liquid phase hydrocarbons (LPH) on the water table along with a dissolved phase plume covering an area of approximately 1000 m². The water table was at 50–60 feet and the free product plume extended across a road and onto an adjacent school property. To compound the problem, fluctuations in water table elevation had caused smearing in the unsaturated tight silty soil immediately above the LNAPL. Because of the depth of the water table, it was decided to employ *in-situ* technologies to remediate the site. A remedial action plan comprising a host of physical and biological techniques was developed for the remediation.

The site remediation began in 1995 with the removal of the 0.5-meter layer of free product on the water table via seven pumping wells. This was done with the help of a pump-and-treat system setup in a bioslurping fashion, which delivered the impacted water and free product to an oil-water separator. The removed water fraction was then directed to a granular activated carbon (GAC) unit for treatment and then discharged to the sanitary sewer. The free product organics were stored on-site in drums and removed periodically. The pump-and-treat system was used to lower the water table and create a temporary LNAPL flow towards the extraction point (cone of influence). By the time this system was combined with more advanced recovery and degradation techniques, it had removed in excess of 7 million liters of impacted groundwater, which, based on mass calculations, represented approximately 4300 liters of the LPH. More importantly, it prevented plume expansion towards the school across the street and significantly reduced the size of the area requiring further treatment.

Upon removing the majority of the free product, it was agreed that further treatment was necessary to remove or degrade the remaining plume as well as the residual contamination present in the soil. A Certificate of Approval (C of A) was obtained for a vapor extraction system (VES) commissioned in December 1996. It was agreed that the VES would run in conjunction with the pump-and-treat system for a full year because their interaction was expected to produce better results than their

independent use. The VES included a combination of air sparging, soil vapor extraction, bioventing, and off-gas treatment using a biofilter.

Used in combination, these technologies opened new design possibilities for product recovery. For this project, the injection of air in the subsurface saturated zone (air sparging) was not only used as a method of physically volatilizing the contaminants, but also to create groundwater mounding. Given that the injection wells are placed around the perimeter of the plume, the groundwater mounding created a type of bowl. This served to physically contain the LPH and create a direct path to the extraction wells positioned in the bowl.

A bioventing/SVE system as well as an air-sparging well were installed in the area of residual soil contamination. Wells were situated to encourage movement of air in the subsurface to SVE recovery wells. This system created airflow sufficient to induce volatilization rather than simply promote aerobic microbial activity. In effect, the simultaneous use of these three methods combines the biological effect of air supply with the physical transport and recovery of the contaminants.

The SVE was installed to remove the vapors resulting from residual product volatilization and to intercept the two contaminated air pathways resulting from air-injection bioventing and air sparging. Based on the results of the consultant's examination using a model called "Venting," it was determined that the horizontal zone of influence would be a radius of approximately 10 meters. The 5-cm diameter PVC extraction tubes were lowered to a depth where they would be approximately 1 meter above the water table and attached to a 5-hp blower located in what is referred to as the support facility. The support facility included the mechanical workings of the treatment processes, the surface treatments (such as the oil-water separator), and the biofilter contaminated air treatment system.

Two biofilters were used to treat the vapor phase contaminants extracted via the VES. A biofilter is an isolated treatment cell filled with compost.¹⁰ In the biofilter, an artificial environment is created where the high specific area of the compost, along with optimum moisture content and high levels of oxygen encourage microbial activity, in turn helping to intercept and degrade the contaminants present in the vapor phase. For this particular application, the cell was built out of metal with dimensions of approximately

¹⁰ Compost can be virtually any organic material that will generate heat as it decays, for example, grasses, wood, sawdust, or leaves, or some types of animal manure.

2.5 x 2.5 x 5.2 meters with rear-loading access doors. A layer of compost 2 meters in thickness was placed as the treatment medium over a 5-cm PVC 20-slot screen distribution system by which the contaminated air was introduced. The lines were covered by a 0.5-meter layer of crushed stone to promote even air distribution throughout the biofilter as well as to ensure full drainage of water. The cell was also equipped with a water distribution system composed of 1-inch "soaker" hoses above the compost to maintain optimum moisture content in the presence of high airflow.

The compost material provides a large surface area where the contaminants are adsorbed and become bio-available to the microorganism population. After careful monitoring, the post-treatment vapors were deemed acceptable for release directly to the atmosphere. At the time the VES was installed, the majority of the LPH had been recovered and noticeable reductions in the plume size had been observed as a result of success with bioslurping. The added benefit of the VES system eliminated the residual hydrocarbons within the 1-year time predicted, and the site, along with its groundwater, was declared clean in October 1999.

Cost Data—Not included.

12. Site 12—Landfarm, Canadian Forces Base Borden, Canada

In 1994, a landfarm was built at CFB Borden to create a central treatment area for impacted soils recovered during the excavation of fuel storage tanks located in personnel quarters on base. The surface area of the operational landfarm is approximately 560 m² and is designed to receive soil of 0.67 meters in thickness.

The landfarm had limited success at its inception, caused by several factors. First, the landfarm was designed with an inadequate drainage system causing the area to flood or become saturated on repeat occasions. The resulting oxygen-deficient environment forced the biological degradation process into anaerobic mode, which is a much slower and less efficient process.

Ideal moisture content for *in-situ* biodegradation varies between 10 percent and 30 percent, depending on the site and its soil characteristics. For soil with high water contents, care should be taken to ensure adequate drainage of the landfarm. Liners and drainage pipes should be installed at the base of the landfarm to prevent saturation from occurring.

Gaps in the geomembrane liner located in the berm walls allowed surface water to flow onto the landfarm. These gaps in the membrane may also have been responsible for allowing contaminants to migrate from the landfarm onto adjacent clean soils.

The cultivation (tilling) program had many problems. Soil in a landfarm should be tilled on a regular basis (e.g., every 2 weeks). However, at this site, the operators encountered challenges ranging from mechanical problems with tractors to scheduling of equipment, resulting in a sporadic and ineffective tilling program. Soil mixing is necessary to ensure that anoxic conditions do not occur. Tilling also provides an opportunity to add nutrients (i.e., fertilizers) to the mixture to help the microorganisms colonize and subsequently consume the contaminants as substrate.

At Borden, the microorganisms were not capable of degrading the hydrocarbons in the soil at the expected rate. In fact, the facility operators reported that it took approximately 18 months per soil cycle to achieve reasonable treatment levels as opposed to less than 1 month for an average, properly managed landfarm in Canada. It was concluded that flooding caused by the inadequate drainage system, the irregular cultivation program, and the erosion of the berms, led to ineffective operation of the landfarm.

In 1998, Base environmental staff developed an informal work plan to address these problems. Their first priority was to repair the berms to prevent any further erosion and, hence, spreading of the contamination. Tests were run on the soil to determine microorganism type and count, and the fertilizer was adjusted to stimulate microbial growth. Finally, the operations made improvements to the drainage system to prevent water accumulation and took measures to correct drainage slope deficiencies to control percolation. The landfarm now is being operated successfully. The lesson here is that although landfarming is a relatively simple process, it still requires solid engineering principles and regular follow-up to be effective.

Cost Data—Not included.

13. Site 13—Landfarm, Lancaster Park Canadian Forces Base, Edmonton, Canada

Hydrocarbon contamination was discovered while upgrading a former bulk fuel storage area housing four above ground storage tanks containing a total of approximately 1 million liters of JP-4 jet fuel. Before the completion of the upgrade program, it was decided that the facility would be decommissioned. The contamination delineation indicated that approximately 20,000 m³ of soil was impacted. The suspect area was

surrounded with a high-density polyethylene (HDPE) containment liner to prevent off-site migration, and a landfarm solution was adopted. Landfarms are popular in Western Canada because sufficient area exists to conduct landfarming operations, and there are no provincial environmental regulations regarding hydrocarbon vapor release.

A site was selected for the landfill. The environmental site assessment performed from 1993 to 1995 indicated the presence of nearly 2 meters of lacustrine clay overlaying a layer of low hydraulic conductivity lacustro-till. The water table depth varied between 0.84 meters and 2.0 meters. Provincial regulations stipulate that the water table must be separated from waste in the landfarm by at least 0.5 meters to prevent groundwater contamination. Given the subsurface strata identified by the environmental site assessment, it was decided (along with the help of provincial environmental regulators) that a clay liner could be constructed near the surface to prevent migration.

Based on the estimated 20,000 m³ of impacted soil, the landfarm was designed to cover 9000 m² of surface area. It was later determined that 35,000 m³ of soil required treatment. The construction of the site was not altered from its initial design, but the landfarm needed to be operated longer than anticipated to treat the additional soil. It was designed and built with a base slope of 1.5–2 percent to provide positive drainage towards surface ponds capable of holding 24 hours of rainfall. This eliminated the need for a subsurface drainage system and assisted in avoiding the problems encountered at CFB Borden. Berms were also constructed out of the compacted clay to a height of 1.0 meter, with a 2.0 meters top width and 3:1 side slopes. A total of 13 monitoring wells were placed outside the perimeter of the berms to ensure that no discharge was occurring, and the landfill is now active. The wells are sampled on a quarterly basis to determine if a leachate problem exists.

The tilling depth within the landfarm is approximately 300 mm. A 610-mm diameter breaking disks rototiller is used to overturn, bust, and aerate the soil to the full depth during cultivation. This process is done 3–4 times per lift of soil. The optimum moisture content in the facility was determined to be between 6–20 percent and is controlled when necessary. The pH is also controlled and is usually kept in the 6–8 range.

The objective of the process is to decrease the concentrations of hydrocarbon components to below the provincial guidelines for industrial/commercial land use. In this case the vapor inhalation pathway is the primary consideration with guidelines as follows: Benzene, 1.5 ppm; Toluene, 340 ppm; Ethylbenzene, 400 ppm; Xylenes, 130

ppm; Total Petroleum Hydrocarbons (Purgeables and Extractables), 4000 ppm. These levels are typically attained within a 7–10 day period at the Lancaster Park landfarm. It is important to note, however, that contaminant volatilization plays a key role in lowering the concentration measured from the soil samples and that Alberta does not have air emission guidelines for hydrocarbon release.

Cost Data—Not included.

14. Site 14—JP-4 Jet Fuel Spill, Air Force Unit, Ängelholm, Sweden

The site, a former aircraft refueling area, is located at an Air Force Unit in Ängelholm, in the southern part of Sweden. Described below is a bioventing study and bioremediation activities conducted at the site of a JP-4 jet fuel spill. Bioventing was combined with the injection of microorganisms and nutrients. The treatment study was carried out in cooperation with the Swedish National Oil Stockpile Agency.

Site Characterization—The soil consists of sand and silty sand with low to moderate permeability. Groundwater table is located around 20 meters below ground surface. The contaminated area is about 200 m² and about 500 m³. Petroleum hydrocarbons have not been detected in the groundwater below the area.

Site investigation revealed the presence of petroleum hydrocarbons in soil samples at concentration level above proposed guideline values from the Swedish EPA concerning “sensitive land use.” The concentrations of carbon dioxide and light hydrocarbons in soil gas were significantly high. According to a toxicological screening test, the soil was classified as “highly toxic.”

Average annual temperature in the area is normally between 5–10 °C and average annual precipitation is around 695 mm.

System Design and Installation—Treatment of contaminated area occurred in two time periods: September–December 1996 (Stage 1) and May–October 1997 (Stage 2).

Venting pipes were installed in six different points within the contaminated area. Initially, venting pipes were screened between 0.3–2.3 meters below ground surface but were later replaced by pipes screened between 1.6–2.7 meters below ground surface. This allowed the injected air to reach the deepest part of the contaminated zone. Air injection occurred 8–16 hours every day with injection flow approximately 1 m³/hour.

To stimulate biological activity in the zone of contamination, nutrients and oil-degrading microorganisms were added to the soil together with water. During both

Stages 1 and 2, approximately 500 liters of nutrients, 2000 liters of enzyme activators and 6 kg of oil-degrading microorganisms were added to the contaminated soil. The nutrient/microorganism/water mix was spread out uniformly over the treatment area.

Monitoring Program—The monitoring program included:

- Soil sampling before and after the treatment period. Soil samples were taken in narrow sampling pits and analyzed for volatile organic compounds (VOC) in the headspace phase. Total petroleum hydrocarbons were divided into aromatic and non-polar aliphatic compounds, and according to toxicity.
- *In situ* respiration tests carried out at two different occasions during the treatment period.
- Monitoring of light alkanes (measured as methane equivalents), carbon dioxide and oxygen in soil gas. Soil gas sampling was done through three perforated steel tubes screened at a depth of 1.6 meters below ground surface.

Results and Preliminary Conclusions—The study suggests that biodegradation has taken place within the contaminated area. Oxygen utilization rates between 0.2–0.5 percent/hour were calculated from the *in situ* respiration tests done on two different occasions. During the treatment period, the concentration of petroleum hydrocarbons has dropped significantly as shown in Table 4. VOC-concentration in the headspace phase above soil samples has been reduced to between 65 and 99 percent during the treatment period. The toxicological screening test carried out before and after the treatment periods show that the soil is significantly less toxic after treatment than before.

The reduction in contaminant levels is assumed to be a result of combined bioventing/soil venting and the injection of nutrients and oil degrading microorganisms. However, passive soil gas sampling carried out during the first stage of the treatment period showed no significant emission of light aromatics during the soil venting activity.

After treatment, the concentrations of aromatic hydrocarbons and non-polar aliphatic hydrocarbons (with only one exception) were well below the proposed guideline values for “sensitive land use,” according to the Swedish EPA.

Estimated and Actual Cost—The cost for full-scale treatment is estimated to be \$20/m³ or \$12/ton. The cost estimation is based on the assumption that the zone of the contamination is restricted to the surface part of the soil profile, approximately 0–3 meters in depth. The Swedish Armed Forces use the equivalent of US\$ 3–5 million each year for this cleanup effort.

**Table 4. A Review of Laboratory Analyses
Carried Out During the Treatment Periods**

Sampling Point (meters)	Non-Polar Aliphatics (mg/kg ds) ^a			Aromatic Hydrocarbons (mg/kg ds)		
	Before Stage 1	After Stage 1	After Stage 2	Before Stage 1	After Stage 1	After Stage 2
1. 1.6-2	220	400	140	130	<7.4	<11
2. 0.5-2	830	1400	800	<110	<23	<35
3. 0.5-2	490	880	130	220	<37	<7.2
4. 0.5-2	420	280	38	240	<5.6	<7.4
5. 0.5-2	1100	540	150	<110	<7.4	<7.9
Mixed sample 1-5	910	410	140	<110	<7.4	<11
Proposed guideline values (Swedish EPA)	MKM ^b 1500	MKM ^b (gw) 1500	KM ^c 200	MKM ^b 100	MKM ^b (gw) 95	KM ^c 38

^a ds = dry soil

^b MKM = less sensitive land use without groundwater; MKM (gw) = less sensitive land use with groundwater

^c KM = sensitive land use.

Documentation—The project was documented in two special reports written by the Johan Helldén AB consulting company. Contact Johan Helldén, Teknikringen IE, 583 30 Linköping, Sweden. Phone 46 13 210294, email: johan.hellden@swipnet.se

15. Site 15—Soil Flushing of a Remote Boreal Forest Diesel Spill, Saskatchewan, Canada

A spill of more than 2000 gallons of diesel occurred on a remote crown-land location in the Northern Boreal Forest of Saskatchewan. The diesel contamination spread into a gravel pad underneath a telecommunications building and off site into the neighboring vegetation. The vegetation is mixed conifer and aspen with shrub and moss growing under the trees. The vegetation was clearly stressed from the spill.

Diesel fuel reached a depth of 3 feet and levels in excess of 20,000 ppm on site. The off-site area had concentrations in excess of 18,000 ppm. Diesel was observed flowing from the site at the edge of the gravel pad. Diesel was also present in significant quantities underneath the buildings, making it difficult to reach the plume directly. The pool of diesel was running underneath the gravel pad, along a rock shelf, and draining off site.

Method and Design—The approach to remediation included the following steps:

- Evaluation of the extent and magnitude of the spill
- Evaluation of the depth of the spill

- Evaluation of the underlying site geology
- Development of a soil flushing program
- Laboratory testing of possible surfactants
- Field implementation and monitoring
- Final reporting and closure.

Site conditions indicated that the site was suitable for soil flushing and bioremediation. The diesel under the building was flushed with a mixture of water and surfactant, causing the diesel to move where it was observed flowing from the edge of the site. A filter pad installed at that point trapped any diesel flushed from the site. A sampling well was installed in the projected path of the diesel plume to collect samples for on-site monitoring during the flushing operation.

Following the flushing, the site was treated with fertilizer to accelerate natural biological degradation of the remaining hydrocarbon. Fertilizer was dissolved in water and flushed under the buildings. Off site, fertilizer was spread by hand in the affected area. Laboratory studies were completed for both treatability with surfactant and for biological degradation modeling.

Results—The fieldwork was initiated in early October 1997. The most effective surfactant had been determined in the laboratory before fieldwork began. All equipment and materials including surfactant, mixing tanks, fertilizer, field test kits, peat moss filter material and other supplies were trucked to site.

The work plan included excavating and installing a peat moss filter at the edge of the site, flushing the site with three volumes of surfactant/water mix, a final flush of the site with fertilizer/water mix, and hand spreading fertilizer in the off-site contamination area.

Approximately 30 minutes after beginning the first surfactant flush, surfactant was observed in the monitoring sump. Initial TPH concentration in the sump was under 50 ppm. During the flushing, TPH in the sump rose steadily reaching a high of about 50,000 ppm half way through the flushing operation. TPH then dropped as the hydrocarbon passed through the sump, reaching a level of about 30 ppm in the sump. The flush liquid was passed through the peat moss filter, which trapped any residual hydrocarbon in the fluid. After flushing, contaminated peat moss was removed from the filter and a clean filter was inserted. The contaminated filter material was taken to a site to be spread on the land and treated.

After the initial treatment, observers saw no diesel flowing off site. Sufficient fertilizer/water mixture, equivalent to one pore volume of the affected area, was sprayed under the buildings on site. The remaining dry fertilizer was spread in the tree area off site.

Discussion—Monitoring was conducted on the site during 1998 and 1999. Soil samples were collected from the gravel pad and off-site contaminated area and analyzed for TPH and BTEX. Visual observations were made regarding plant growth off site and movement of diesel fuel off site.

The soil samples indicate that the project was very successful. BTEX levels were below detectable levels. TPH showed a substantive drop across all contaminated areas. In the off-site contaminated areas, TPH reached concentration of 18,000 ppm before treatment. After treatment, this concentration had dropped to 800 ppm.

Cost Data—Not included.

16. Site 16—Canadian Forces Base Trenton: Air Sparging of BTEX, Impacted Soil Using a Gas Liquid Reactor

A Gas Liquid Reactor (GLR) unit and associated equipment was installed at CFB Trenton for the Department of National Defence (DND). The GLR is a patented gas/liquid contactor designed to supersaturate liquids with a specific gas. A fluid dynamic process is used to generate shear, impaction, and pressure, creating micro-bubbles. A liquid containing entrained gas is passed through the GLR unit, resulting in the production of bubbles with a diameter ranging from 5 to 50 μm . By creating small bubbles, the mass transfer area between the gas and liquid phases is maximized, increasing the efficiency of the transfer of the gas to the liquid.

The specific site to be treated at CFB Trenton was a former service station site, contaminated with BTEX from leaking underground storage tanks. Previous soil remediation and source removal had limited efficiency because the majority of contaminated material was located under the service station structure. The objective of this installation was to demonstrate to DND the effectiveness with which the GLR unit can add oxygen to groundwater, thereby stimulating bacterial activity and reducing BTEX and hydrocarbons.

Five groundwater monitoring wells were previously installed at this site, two of which are located within the service building. One large-diameter groundwater recovery

well (30-cm culverts) had also been installed. The contamination had existed at this site for many years prior to remediation activities being undertaken.

A single GLR unit is currently installed without a recirculation tank. A jet pump takes water directly from the recovery well, sends it through the GLR unit, and back into the recovery well. This means the recovery well serves the purpose of the recirculation tank, simplifying the system and oxygenating the groundwater in the immediate vicinity of the recovery well. One throttled injection line runs from the GLR outlet (recirculation line) to the injection point. All injection and recovery lines were retrofitted to existing wells.

Bacterial activity increased significantly at the site, with a corresponding decrease in BTEX and petroleum hydrocarbons, as shown by samples taken from the monitoring wells on the site. Bacterial activity increased significantly in all monitoring wells except the injection well MW11. BTEX concentrations decreased in all wells, as did TPH. Dissolved oxygen levels measured in the monitoring wells and recovery well also increased over the test period. Dissolved oxygen increased dramatically in monitoring wells 11 and 15. MW11 is the injection point and is expected to be elevated. MW15 is midway between MW11 and the recovery well. This indicates that the system has also successfully induced groundwater flow between the recovery and injection points. Smaller increases in the other monitoring wells indicate that the radius of influence extends in directions other than the direction induced by the recovery well.

Cost Data—Not included.

17. Site 17—Canadian Forces Support Unit Former Fire Fighting Training Area, Ontario, Canada—Jet Fuel Natural Attenuation Project

In 1995, one of the first detailed monitored Natural Attenuation studies was completed by the Department of National Defence at the Canadian Forces Support Unit's former Fire Fighter Training Area (FFTA) located at the Macdonald-Cartier International Airport, Ottawa, Ontario, Canada. This study included site characterization and interpretation of contaminant distribution, evaluation of natural attenuation as a remedial option for hydrocarbon (jet fuel) impacted groundwater, applications of computer modeling, and a quantitative risk assessment.

Review of Monitored Natural Attenuation—Natural attenuation is achieved when naturally occurring processes bring about a reduction in the total mass of a contaminant dissolved in groundwater or residual soil fraction. The primary objective for

the evaluation of natural attenuation is to show that natural *in-situ* processes will reduce contaminant concentrations in groundwater to below regulatory standards before potential exposure pathways are completed to sensitive receptors (e.g., water supply wells, rivers and lakes). Natural attenuation of groundwater is typically the primary focus of these studies because groundwater is usually the most significant pathway that transports petroleum hydrocarbon releases to potential sensitive receptors. The *in-situ* processes that determine the rate of groundwater contaminant migration and natural attenuation are advection, dilution, diffusion, dispersion, sorption, biodegradation, and volatilization. All processes except advection can bring about lower impacted groundwater concentrations and, therefore, can contribute to natural attenuation or intrinsic remediation.

Site Setting and Historical Use—The site is covered with sand and gravel, is relatively flat, and covers an area of approximately 75 x 75 meters. In the center of the FFTA, a large tank was installed to simulate a burning aircraft fuselage. This is referred to as the mock-up area. The FFTA operation generally consisted of spraying jet fuel on the large tank located in the center of the FFTA and lighting it for the purpose of extinguishing the fire using standard emergency procedures. The fires were typically extinguished with either fire-fighting foams or dry chemicals. The FFTA was in operation for almost 25 years. In 1992, the site was closed to fire-fighting training activities. Approximately four burns per month were completed where as much as 3500 liters of jet fuel were sprayed and burned. As a result, up to 160,000 liters of jet fuel were used yearly for this training operation with no fuel collection system.

Site Geology and Hydrogeology—In general, the site geology, in descending order, is as follows:

- Surface topsoil with sand and gravel
- Native silty sand with trace gravel
- Limestone bedrock.

Representative soil samples collected at or beneath the water table indicated that the native silty sand typically contains less than 1 percent gravel, approximately 70–80 percent sand, and 25–30 percent silt and clay-size particles. Local historical well records indicate that the thickness of the overburden materials within the vicinity of the FFTA is greater than 30 meters.

The FFTA is situated on a recharge area consisting of fine sand and gravel deposits in a shallow marine environment. Data recorded from the boreholes suggest that

the three geological units can be divided in two local units: an upper unconfined sand unit and a lower limestone bedrock aquifer.

On average, depth to the water table is approximately 8.5 meters below grade. Groundwater flow directions are consistently to the north with radial flow to the northwest and northeast. The calculated horizontal gradient ranges from approximately 0.003–0.005 m/m. Using a calculated geometric hydraulic conductivity (K) average of 7.8×10^{-4} cm/second, an assumed porosity of 0.3 (n) and a gradient of 0.005 (i), the average horizontal groundwater velocity was estimated to be approximately 4–5 meters/year.

Environmental Site Assessment and Remedial Activities—Numerous environmental site assessments have been completed at the FFTA since 1990. The studies ranged from early electromagnetic surveys and limited soil sampling to detailed hydrogeological studies and remedial action planning. Following the environmental assessments, DND proceeded with soil remediation activities in April 1994 to treat the most impacted soil on site. The remediation technique employed to clean up the hydrocarbon-contaminated soil was Low Temperature Thermal Desorption. The site remediation activities included the excavation and treatment of approximately 5900 tonnes covering an area of approximately 1100 m² to a depth of 8.5 m; recovery of approximately 21,893 liters of contaminated groundwater and LPH; and installation of two recovery wells and a recovery trench. Following the soil remediation, additional monitoring-well installations and free-product monitoring and groundwater chemical testing were completed for closeout soil remediation reporting.

Contaminant Assessment—Liquid petroleum hydrocarbons were observed over time beneath the mock up area of the FFTA. Following soil remediation activities (Low Temperature Thermal Desorption) in the spring of 1994 and the installation of a LPH recovery system, only a small volume (<200 liters) of LPH remained as an immobile lens. Chemical analyses of groundwater have indicated that petroleum hydrocarbon parameters exceeded Drinking Water Objectives (DWOs) within and slightly down gradient of the FFTA. Groundwater chemistry (since 1991–1995) has shown significant reduction in the mass of dissolved phase petroleum hydrocarbons over time. In addition, groundwater impacts have not been detected off site and, as of 1995, there was evidence that the groundwater plume was shrinking.

Detailed sampling was completed in March 2000 (5 years following the original assessment) to reevaluate the groundwater impacts. Eleven monitoring wells were

sampled for BTEX/TPH and inorganic parameters dissolved in groundwater, consistent with previous monitoring rounds. Only one monitoring well (BH95-2), located approximately 10 meters down gradient of the FFTA, had detectable concentrations of petroleum hydrocarbons. The concentrations reported were below the DWOs with the exception of ethylbenzene. No LPH was found on site, but it should be assumed to be present as a discrete lens considering that the water levels were below the screen levels of two recovery wells. Analysis of several factors beginning in December 1991 (before remediation) to March 2000 (5 years after remediation) clearly showed a decrease in BTEX mass and size of plume. This analysis was significant because it provides direct evidence that the concentrations and mass of hydrocarbons have decreased with time.

Natural Attenuation Assessment—Biodegradation of BTEX/TPH parameters by indigenous subsurface microbes appeared to be the primary mechanism for attenuation and mass loss at documented sites. During biodegradation, microbes transform available nutrients, including hydrocarbons, into forms useful for energy and cell reproduction. Microbes obtain this energy by facilitating the transfer of electrons from electron donors to electron acceptors. This results in the oxidation of electron donors and the reduction of electron acceptors. Electron donors include natural organic material and petroleum hydrocarbons. Electron acceptors in groundwater include: dissolved oxygen, nitrate, Fe (III), sulfate, and carbon dioxide.

The use of electron donors by microbes begins with dissolved oxygen (aerobic conditions) followed by anaerobic electron donors namely nitrate, Fe (III), sulfate, and, under extremely reducing conditions, carbon dioxide for methanogenesis. Two treatment zones for natural attenuation of hydrocarbons are defined: aerobic and anaerobic.

An evaluation of the natural attenuation processes occurring at the site in 1995 identified aerobic (oxygen rich) and anaerobic (oxygen depleted) treatment zones. The anaerobic treatment zone was occurring beneath the mock up area of the FFTA. This was based on the relationship of depressed dissolved oxygen, nitrate, Fe III, and sulphate concentrations. Aerobic biodegradation was occurring down gradient from the mock up area. This aerobic treatment zone was based on the concentrations of elevated dissolved oxygen concentrations along the groundwater flow path. Further, the software model, BIOPLUME II, suggested that the BTEX plume would continue to shrink over time with only residual local impacts over the next 10 years. In addition, the aerobic treatment zone will displace the anaerobic treatment zone as the BTEX plume is attenuated with time.

In 2000, an evaluation of the natural attenuation processes occurring at the site identified similar aerobic and anaerobic treatment zones as reported in 1995. The anaerobic treatment zone was occurring beneath the mock up area of the FFTA. This is based on the relationship of depressed dissolved oxygen, nitrate and iron. The major difference between the 1995 and 2000 treatment zone studies is that the reducing conditions are at the level where iron reduction will occur. In 1995, the site was more strongly reducing to sulphate reduction. Aerobic biodegradation is occurring down gradient from the mock up area. This aerobic treatment zone is based on the concentrations of elevated dissolved oxygen concentrations along the groundwater flow path.

Conclusion—At this site, the use of natural attenuation has been supported as the preferred remedial option by demonstrating that the dissolved phase plume is shrinking with time and the identification of an aerobic and anaerobic treatment zone. These treatment zones will continue to naturally prohibit the migration of petroleum hydrocarbons down gradient from the FFTA.

The interface between the anaerobic and aerobic treatment zones changes, depending on groundwater fluctuations, seasonal trends, and contaminant dissolution.

An evaluation of intrinsic remediation identified aerobic and anaerobic treatment zones that will naturally manage the fate and transport of the dissolved phase BTEX/TPH plume. The assimilation capacity of the treatment zones has unrestricted capabilities to biodegrade BTEX/TPH parameters. As a result, exposure pathways to potential drinking water receptors will not be completed.

Groundwater flow and transport modeling indicate that the water supply wells are not threatened by the remaining residual impacts at the FFTA. In addition, BIOPLUME modeling has shown that the impacts to the environment will decrease significantly over the next 10 years.

Cost Data—Not included.

18. Site 18—Canadian Forces Base Cold Lake: Low Temperature Thermal Desorption of Fuel Hydrocarbon and Chlorinated Solvents Contaminated Soil¹¹

In March and April 1998, approximately 9300 metric tonnes of contaminated soil were remediated at the Canadian Forces military base in Cold Lake, Alberta. The soil was contaminated with petroleum hydrocarbons, ethylene glycol, trichloroethylene, and phenol, stockpiled in various locations. The soil was treated with a mobile Low Temperature Thermal Desorption (LTTD) technology near one of the stockpiles. The system operated on a 24-hour-per-day schedule without disturbance to surrounding military operations. The LTTD operations occurred within 300 meters of the main aircraft runway used by military fighter jets and transport planes.

Samples of the treated soil were sent to an independent laboratory for analysis to confirm that the LTTD technology was remediating the soil to below the regulated criteria. The laboratory results indicated that all samples were below alluvial levels. Alberta Environment guidelines, Canadian Council of Ministers' of the Environment protocols, and Environment Canada's Technical Assistance Bulletins were adhered to throughout the project.

The contractor doing the remediation was responsible for all soil remediation activities at the site, including the screening and sorting of stockpiled material, treating of the contaminated soil, and disposal of screened material. Upon completion of LTTD operations, the site was restored to the users specifications, including grading the affected areas.

Cost Data—Not included.

For additional information on the Canadian case studies, please contact:

Captain Darrin McMullin
Director General Environment
National Defence Headquarters
Major General Pearkes Building
1010 Colonel By Drive
Ottawa, Ontario
Canada K1A 0K2

¹¹ This site is included in the chlorinated solvents section as well.

B. TECHNOLOGY DEVELOPMENTS AND PILOT SCALE STUDIES

1. Site 1—Valdaisky State National Park, Russia

Objective—To develop a technology to remediate territory contaminated with heavy oil products (fuel oil) and experimentally test it during the environmental restoration of the Valdaisky State National Park in areas where troop units had been stationed.

Tasks

- To conduct a scientific-technical analysis of modern methods and means for remediating soils and reservoirs contaminated with oil products and to create the basis for selecting priority remediation approaches
- To develop an integrated technology for remediating soils contaminated with oil products
- To develop an integrated technology for remediating internal/domestic reservoirs contaminated with oil products
- To develop technical regulations for remediating soils and reservoirs contaminated with heavy oil products
- To conduct experimental testing of these technologies for remediating soils and reservoirs contaminated with heavy oil products at the contaminated area of the Valdaisky National Park in areas where troop units were formerly stationed (Military Towns 1 and 4)
- To conduct a technical-economic assessment of these technologies
- To prepare a recommendation for the Chief of the Ecological Security Directorate of the Russian Armed Forces on introducing these technologies into the ecological security system of the Russian Federation Armed Forces.

Stage I (January–December 1997)—A scientific-technical analysis and systemization of modern methods and means for remediating soils and reservoirs contaminated with oil products was conducted and priority remediation approaches selected.

The technology for remediating soils and reservoirs contaminated with heavy oil products was developed.

Experimental testing of these technologies was carried out at a contaminated site. The remediation of Military Town 1 involved removing contaminated soils, transporting them to a recultivation area (beyond the borders of the military town), and remediating soils and reservoirs *in situ* (in the military town).

Cost for This Stage—900,000 rubles (US\$ 58,065).

Stage II (January–December 1998)—The technological regulations for remediating soils and reservoirs contaminated with heavy oil products were developed.

Experimental testing of the technologies was completed. The remediation of Military Town 1 and remediation of Military Town 4 involved removing contaminated soils, transporting them to recultivation areas (beyond the borders of the military towns), and remediating soil and reservoirs *in situ* (in the military towns).

A technical-economic assessment of these technologies was conducted.

Recommendations were developed to introduce these technologies into the ecological security system of the Russian Federation Armed Forces.

Cost of This Stage—900,000 rubles. (US\$ 58,064).

Anticipated Results—Technological regulations for remediating soil and reservoirs contaminated with heavy oil products, coordinated with the Russian Federation State Ecological Committee (with an annex, Act on the Results of Testing Technologies in Valdaisky National Park).

Remediation of soils and reservoirs of the Military Towns 1 and 4 (3.2 hectares and 1.51 hectares, respectively) in Valdaisky National Park (Act on the Acceptance of Remediated Territory by Local Environmental Protection Authorities).

Contaminated soil in recultivation areas beyond the borders of the military towns.

Main Contractor—Polinform (St. Petersburg).

2. Site 2—Engels Air Force Base, Russia

Development of a range of probes and technologies for detecting, monitoring, and extracting a pool of oil products from soil, based on the experience of Engels Air Force Base.

Objective—To create a maximally effective complex of technologies available in Russia, both analytical and manufactured technologies for detecting, monitoring, and eliminating oil product contamination.

Tasks

- To analyze and summarize the results of research conducted on the Engels facility and to develop a program for field work

- To do ecological and hydrogeological field work in order to clarify the parameters of the facility
- To create a three-dimensional model of oil product contamination
- To develop a statement of work for the project to eliminate contamination and recultivate soils
- To select, on the basis of serially manufactured equipment, a rational mixture of various technologies that will detect, monitor, and eliminate light oil product contamination, including the extraction of underground oil product accumulations in pools of oil
- To take practical steps to perfect technologies that would remediate or localize the hot spots contaminated with jet fuel at the Engels military facility
- To develop methodological recommendations on monitoring and remediating military sites contaminated with light oil products.

Stage I (January–December 1998)—An analysis and summary of the results of the research conducted at Engels was carried out and a fieldwork program developed. Environmental and hydrogeological fieldwork clarified the basic parameters of the contaminated site so as to develop the project for remediating the territory. A three-dimensional model of soil contaminated with oil products was constructed to develop the project for remediating the territory. The selection of necessary and rational technologies and a range of technologies for detecting, monitoring, and eliminating kerosene contamination are substantiated.

Cost for This Stage—350,000 rubles (US\$ 22,580).

Stage II (January–December 1999)—A project was developed to eliminate oil product contamination of soil layers and restore it environmentally. First, the project to remediate the territory was approved by local environmental protection authorities. Second, the statement of work for the project to eliminate oil product contamination was developed. Practical steps were carried out to finalize technologies that would remediate or localize the hot spots contaminated with jet fuel at the Engels military facility. Methodological recommendations were then developed on monitoring contamination and remediating military sites contaminated with light oil products. Finally, tactical-technical requirements were developed and approved for a range of technologies for detecting, monitoring and eliminating oil product contamination.

Cost for This Stage—500,000 rubles (US\$ 32,258).

Anticipated Results

- The substantiation of an optimal range of technologies for a remediation project.
- A three-dimensional model for oil-contaminated soil in order to develop a remediation project.
- A project approved by local environmental protection authorities for eliminating the layers of soil contaminated with oil products and environmentally restoring the soil.
- A statement of work (SOW), coordinated with the customer, for the project to eliminate oil product contamination and recultivate the soil.
- Acts/documents to accept the remediated portions of the territory or the results of the work to localize dangerous contamination hot spots, approved by local environmental protection authorities.
- Methodological recommendations on monitoring and remediation of territory contaminated with light oil products.
- Tactical-technical requirements for a range of technologies for detecting, monitoring and eliminating oil product contamination.

Main Implementor—Institute on Oil and Gas Problems, Russian Academy of Sciences (Moscow).

3. Site 3—General Use on Military Bases in Russia

An integrated method is being developed for assessing environmental ground conditions where troops and sailors are stationed, along with methods for improving such conditions.

Objective—The development of an integrated assessment of the environmental ground conditions where troops and sailors are stationed and a method for improving these conditions.

Tasks

- To develop methods for an integrated assessment of the environmental ground conditions where the Russian Armed Forces are stationed
- To develop a mathematical model for an integrated assessment of the environmental ground conditions in areas when Russian Armed Forces are stationed
- To issue methods for an integrated assessment of the environmental ground conditions where ground, missile, and air force troops are stationed and to

provide an environmental protection inspection of branches of the Armed Forces, districts, troop arms, and the main and central directorates of the Russian Ministry of Defense

- To develop guidance on methods for monitoring missile fuel, explosives, and artillery gunpowder in the soil and water
- To develop systematic recommendations on improving the ground in areas where Russian military forces are stationed
- To compile a package of standardized technical documents, necessary for carrying out environmental inspections and remediation of military garrisons in Arctic conditions.

Anticipated Results

- A pilot model unit for remediation
- An effective technology for cleaning soil, water, and various wastes and garbage contaminated with POL, extracted POL, and water disposal technologies, the processing and elimination of wastes and garbage
- Instructions/directions on the operation of a pilot model remediation facility
- A draft SOW on design of an experimental-production facility
- Temporary standards for permissible levels of oil and hydrocarbon contamination at military facilities and in their internal reservoirs.

Main Contractor—The State Scientific Center of the Russian Federation, TsNIIKhM, Moscow.

Stage I (January–December 1998)—First, a scientific-technical analysis was conducted, current methods and technologies for cleaning up soil and reservoirs contaminated with oil products (POL) were systematized, and the priority direction for cleanup selected. Second, working designs for a pilot model for a standardized mobile modularized remediation complex developed. Third, technological diagrams for module POL cleanup of soils and reservoirs developed. Then a pilot model of a remediation complex was prepared at the factory. Finally, temporary standards for permissible levels of oil and hydrocarbon contamination at military facilities and in their internal reservoirs are developed, substantiated, and agreed to with the State Ecological Committee.

Cost of This Stage—900,000 rubles (US\$ 58,064).

Stage II (January–December 1998)—First a program for experimental testing of the effectiveness and reliability of the pilot model for a mobile cleanup complex at military facilities was developed. Second, experimental field-testing of the pilot model

for the mobile cleanup complex was carried out. A draft statement of work on experimental design work of an experimental-production facility was developed. Then technical changes to individual units of the module were introduced. An integrated technical-economic assessment of the effectiveness of the pilot model for a mobile cleanup complex was then carried out. Finally, recommendations to introduce a mobile cleanup complex into the environmental security system of the Russian Armed Forces were developed.

Cost of This Stage—1,000,000 rubles (US\$ 64,516).

4. Site 4—General Use on Military Bases in Russia

Objective—To substantiate ways of creating a mobile, standardized, automated production complex using non-waste generating technology for POL cleanup of territories and internal water areas.

Tasks

- To conduct a scientific-technical analysis and systematize current methods and technologies for cleaning up POL-contaminated soil and reservoirs and to substantiate the selection of priority directions for cleanup
- To develop an integrated technology for module cleanup of POL-contaminated soil and reservoirs
- To develop a principle working diagram for a mobile, standardized, modularized complex using non-waste generating technology
- To develop working designs for a remediation complex for factory production of the pilot model
- To conduct field-testing of the effectiveness and reliability of the pilot model at military facilities and to make technical corrections in individual units of the module
- To develop a draft statement of work on experimental design work of an experimental-production facility
- To develop, substantiate, and reach agreement with the State Committee on Ecology on temporary standards for permissible levels of oil and hydrocarbon contamination at military facilities and in their internal reservoirs.

Anticipated Results

- Methods for monitoring the components of missile fuel, explosives, and artillery gunpowder in the soil and water

- Methods for an integrated assessment of the environmental ground conditions where Russian ground, missile, and air force troops are stationed
- Methodological recommendations on improving environmental conditions in areas where Russian military forces are stationed
- A package of standardized technical documents, necessary for carrying out environmental inspections and cleaning military garrison areas in Arctic conditions.

Effect From Doing This Work—Ensuring that the contamination from missile fuel, explosives, and artillery gunpowder are determined in order to monitor the technical conditions of facilities with missile fuel and explosives and to assess the effectiveness of improving them without spending money on calling in outside organizations.

Main Contractor—The Association of Agro-Chemical, Soil, Ecological, and Aerospace Analysis in Agriculture (APEK), Moscow.

Stage I (January–December 1996)

- Selecting the directions for research
- Developing the methods
- Dividing up the leadership and mathematical model within the integrated program.

Cost—Unknown.

Stage II (January 1997–December 1997)—Theoretical and experimental research:

- Determining the list of priority contaminants where Russian Armed Forces troops are stationed, developing a methodology for monitoring them and methodological recommendations for improving the land
- Creating an experimental stand for mathematically processing the results of evaluating the environmental condition of the land in areas where Russian Armed Forces troops are stationed.

Cost—Unknown.

Stage III (January 1998–December 1998)

- Synthesizing and evaluating the results of the research
- Implementing and coordinating methods of leadership
- Publishing scientific-technical documentation.

Cost Data—Not included.

5. Site 5—CFB Borden, Canada, Naphthalene Plume Control

In a 1990 pilot test to develop remediation of chlorinated solvents, coal tar creosote was placed below the water table in the sand aquifer at CFB Borden to create a dissolved phase plume, which included phenolics, xylenes, and naphthalene. Although very mobile constituents such as phenolics and xylenes were removed by natural attenuation, the plume of unremediated naphthalene continued to expand. Therefore, a pilot-scale Funnel & Gate (F&G) was installed in 1997 to limit the expansion of the naphthalene plume. The F&G was a Waterloo Barrier™ sealable sheet piling and the gate made use of a novel cassette system with four removable sections. Each cassette was 2.4 x 0.8 x 0.5 meters. Two rows of four cassettes were stacked in the gate like short columns on their 0.8 x 0.5 meters ends. The plume would thus first encounter a 4.8 x 0.8 meters “face” of the first two cassettes in the gate, then flow through a total of eight cassettes (four in each row).

The purpose of the funnel-and-gate cassette design was to test a novel denitrification approach to naphthalene treatment. The first two cassettes in each row, each named cassette 1, contained small concrete briquettes, which were designed to release nitrates into the plume flow, thus assisting the denitrification of naphthalene in the gate. The briquettes were manufactured with ammonium nitrate made specifically to minimize the high pH associated with concrete. Nitrate release came from these concrete briquettes, as shown by the nitrate detection in the passing groundwater. A microbial consortium was inoculated into cassettes 2, 3, and 4 of each row. (The microbial consortium was developed from Borden aquifer material and capable of degrading naphthalene under denitrifying conditions.) Each of these six cassettes was also filled with sand and granular activated carbon.

Since the hydraulic parameters of this aquifer were known, the plume capture by the F&G could be predicted using simple flow models (Visual MODFLOW, version 2.00, 1995, in this case). The F&G was “hanging”; that is, it did not touch the underlying aquitard. In many cases, this can produce considerable cost saving but may allow a plume to flow underneath the system. The modeling suggested the section (across flow) of groundwater captured would be triangular. As predicted, the naphthalene plume is not plunging but proceeding directly into the gate at the same depth as it occurred in the aquifer.

A novel aspect of treatment was the use of denitrification for naphthalene removal in the gate. Nitrate release was from concrete briquettes manufactured with ammonium

nitrate made specifically to minimize high-pH associated with concrete. The briquettes were placed into cassette 1, lowest in the subsurface of four cassettes, and were shown to release nitrate into the passing groundwater. A microbial consortium, developed from Borden aquifer material and capable of degrading naphthalene under denitrifying conditions, was inoculated into cassettes 2, 3, and 4, each filled with sand and granular activated carbon. These cassettes were stacked above number 1.

The groundwater containing the naphthalene plume flowed into the cassette system. Naphthalene was initially persistent into the third cassette in each row. Naphthalene concentrations declined from 2.2–0.3 mg/L up gradient of the briquettes, to 0.9–0.2 mg/L immediately after the briquettes, to < 0.2 mg/L after the second sand GAC cassette, and naphthalene was not detected (< 0.01 mg/L) after the last cassette. In 1998, neither nitrate nor naphthalene persisted beyond the first cassette. The nitrate-releasing briquettes had developed a biofilm at a depth consistent with maximum naphthalene concentrations. Denitrifying, naphthalene degraders established themselves in the first cassette in each row and remediated the naphthalene.

After naphthalene attenuation was observed slightly up gradient of the briquettes, the gate was reconfigured in June 1998. A simple sand cassette was placed up gradient of the briquette cassette. Further characterization of microorganisms in the pea gravel zone up gradient of the cassettes and within the briquette cassette indicates that aerobic bacteria were mainly responsible for naphthalene attenuation. Apparently, oxygen-bearing groundwater within, above, or below the naphthalene plume was mixing with oxygen-poor, naphthalene-bearing plume water. Therefore, aerobic naphthalene degradation may have been sufficient for complete attenuation even before the cassette gate treatment. Additional field sampling is underway to evaluate this idea.

As predicted in the design modeling, the hanging design did not produce a plunging naphthalene plume. A tracer test in the gate determined an estimate of the groundwater flux through the gate, and the flux appears greater than predicted in design modeling. Evaluation of the predicted migration of naphthalene around the funnel continues.

Cost Data—Not included.

6. Site 6—CFB Calgary, Canada, Electron-Thermal Dynamic Stripping Pilot Test

Between February and June 1999, a pilot test of an *in situ* fuel hydrocarbon remediation process known as electro-thermal dynamic stripping (ETDS) was carried out

at the former CFB Calgary CANEX service station in Calgary, Alberta. The test area occupied approximately 315 m² and the average thickness of soil affected with petroleum hydrocarbons was approximately 1.5 meters at a depth of 4.2 meters below grade. The ETDS was used to increase the subsurface soil temperature in the zone of contamination by resistance heating as a result of passing an electric current through the saturated soil. The higher subsurface soil temperature increased the vapor pressure of organic chemical contaminants resulting in enhanced volatilization of the organic compounds. By increasing the vapor pressure, the organic chemical compounds were more easily desorbed from the soils and recovered in either the dissolved phase or the vapor phase by extraction equipment; a dual phase extraction (or bioslurping) process was used for vapor and liquid recovery.

The soil heating system consisted of a transformer, an electrode assembly, and an electrode cooling system. Six electrodes were installed in a 2 x 3 matrix with 2 separate rows approximately 9 meters apart, with 7 meters spacing within the rows. Each electrode consisted of a 1.5-meters steel electrode and a 4-meter long high-temperature fiberglass pipe. The electrodes were installed to a depth of approximately 4 meters below grade and extended 1.5 meters above grade. The electrodes were placed within each 300-mm diameter borehole, backfilled with granular graphite to approximately 2.5 meters below grade and then sealed with bentonite to grade. Electricity was supplied to 3 (hot) electrodes at a time while the remaining 3 electrodes acted as neutrals. To create a uniform heating pattern within the electrode array, the hot electrodes and neutral electrodes were switched 9 times over the 116 days of the ETDS pilot test. The rate of cooling water flow and the applied current were adjusted such that the temperature at each electrode did not exceed 95 °C.

Two different extraction systems were used during the pilot study. From 16 February until 21 May 1999, a 7.5-hp liquid ring pump and a 3-hp regenerative vacuum unit were used. From 21 May to 21 June 1999, a 30-hp rotary positive displacement blower unit was operated.

The average temperature of the ground on 10 February 1999, prior to activating the ETDS equipment, ranged from a high of 7.3 °C at a depth of 3.5 meters to a low of 1.2 °C at a depth of 1.5 meters. Measurements indicate that the temperature of the soil at 3.5 meters below grade within a 2-meter radius of each electrode increased 45 °C within the first 40 days of heating. Over the next 60 days, the average increase in temperature was 20 °C. Over the last 20 days of the pilot test, the average change in temperature decreased with only the center portion of the array showing an increase in temperature.

The change in temperature outside the 2 meters radii increased at a slower rate for a final average of 42 °C at the conclusion of the pilot test. The temperatures of the soils within the electrode array after the system was deactivated decreased at an average rate of approximately 0.25 °C per day.

From 16 February through 20 May 1999, the leakage rate from the electrode cooling system often exceeded the groundwater recovery rate of the extraction system. This resulted in a groundwater table as high as 0.7 meters below grade. After 21 May 1999, the depth to groundwater within the extraction wells averaged 5 meters below grade.

Subsurface petroleum vapor concentrations increased from <5 ppm to 35 percent lower explosive limit (LEL) once the in-ground temperatures increased to approximately 40 °C and up to >100 percent LEL after the temperatures reached 70 °C.

Within the test area prior to activation of the ETDS, benzene concentrations ranged from 1 mg/kg up to 8.5 mg/kg with an average benzene concentration of 2.4 mg/kg. Over the duration of the pilot test, benzene concentrations decreased with time. The average benzene concentration in the March 1999 samples was 4 mg/kg; in the April–May 1999 samples, 3.7 mg/kg; and in the June 1999 samples, 1.7 mg/kg. Data evaluation suggests a reduction in the mass of benzene of approximately 73 percent during the pilot test.

Increased mobility of the petroleum hydrocarbons in the test area resulted not only in increased vapor hydrocarbon concentrations, but also in increased hydrocarbon concentrations in groundwater. For example, at one location, the benzene concentrations in groundwater increased an order of magnitude when the temperature increased to approximately 30 °C. During the EDTS pilot test, increased subsurface soil temperatures increased the benzene vapor concentrations by as much as 6 times. The vapor extraction equipment removed a total of approximately 140 kg of petroleum hydrocarbons from the subsurface over the period from 16 February through 26 June 1999 for an average extraction rate of 1.1 kg/day. It is estimated that as much as 200 kg of petroleum hydrocarbons were present in the subsurface prior to activating the ETDS system. Therefore, over this 132-day period, the system successfully extracted approximately 74 percent of the total mass of BTEX. It should be noted that in the final 36 days of extraction, after the larger system was installed, the equipment removed an average of 2.3 kg/day (3.3 L/day) or approximately 58 percent of the total quantity of hydrocarbons removed. The reason for this increased rate was that the larger system could effectively

lower the groundwater table in more wells within the electrode array to a level beneath the zone of affected soils. With the lower groundwater table, air could pass through the previously saturated zone removing the hydrocarbons from the heated soils. These soils had remained saturated during the operation of the smaller system, thereby relying on slower removal of dissolved-phase hydrocarbons from the groundwater via diffusion.

7. Site 7—Canadian Forces Base Calgary, Alberta, Canada: Vacuum-Enhanced Liquid Recovery Pilot Test

In 1997, a pilot test was performed at a CFB Calgary former CANEX service station as part of a series of tests aimed at estimating the feasibility of various *in-situ* remediation techniques beneath the site. The site geology consists of a 15-meters-thick layer of glacial lacustrine sediments comprising mainly of silts and clays, deposited on bedrock materials consisting of shale or sandstone. In May 1997, the average depth to the groundwater table was 3.3 meters below grade. The site facilities previously included five 22,700-liter underground petroleum storage tanks and two pump islands. These structures were excavated and removed in 1995.

On October 15, 1997, site investigation revealed the presence of liquid hydrocarbons in 2 of the 21 boreholes (BH) drilled for purposes of investigation. Respectively, BH1 and BH6 contained 611 mm and 144 mm of liquid hydrocarbons (apparent thickness).

The vacuum-enhanced liquid-recovery pilot test was performed using a 25-hp liquid ring pump capable of removing air at a rate of 1100 l/min (standardized to 1 atmosphere) at a vacuum of 650-mm Hg, with an average liquid flow rate of 30 L/min. The system consisted of a liquid separator tank, a 25-hp liquid ring pump, a heat exchanger, a liquid knock out/vapor exhaust drum, an air stripper, and a discharge pump. The discharge line was equipped with a flow totalizer and was connected to a 35,000-liter above grade holding tank.

The unit was connected to one of the 21 boreholes, and vacuum responses were observed in 11 of the other boreholes. The extraction well was constructed of 75-mm diameter PVC pipe slotted from 1.5–6.1 meters below grade. The observation wells were constructed of either 75-mm or 50-mm diameter PVC pipe slotted from approximately 1.2 meters to approximately 6–7 meters below grade. The lithology in the immediate vicinity of the extraction well consisted of silt, sand, and gravel fills overlying native silt materials at 3.5 meters below grade.

The recovery line was constructed of a 25-mm-diameter high-density polyethylene (HDPE) hose sealed to the wellhead of the recovery well. Pressure gauges and groundwater level sounders were used at the extraction and observation wells to measure the vacuum responses and liquid drawdown, respectively.

Once the system was installed, two separate tests were performed at the site. On October 15, 1997, a step test was performed on the recovery well. This test was specified to increase the vacuum applied to the wellhead at pre-determined intervals while monitoring the liquid drawdown and pressure changes in the observation wells. Opening and closing air dilution valves located on the extraction well and the liquid ring intake port controlled the wellhead vacuum. Each individual step was terminated, and the next step initiated once the vacuum head distribution was observed to stabilize at pseudo steady state.

Immediately following the step test, from October 23rd to 26th, a long-term vacuum enhanced liquid recovery test was performed on the recovery well. This test was performed with all the dilution valves closed enabling the system to stabilize at full vacuum. It should be noted that a maximum system vacuum would be dependent on the permeability of the formation up to a maximum of approximately 725-mm Hg.

Results of the Step Test—The vacuum heads applied during the step test were 55-mm Hg, 110-mm Hg, 160-mm Hg, 200-mm Hg, and full unit vacuum (approximately 425–525-mm Hg measured at the system). Note that the first three portions of the test were designed to mimic conventional vapor extraction. This will enable us to determine if vapor extraction may be a better alternative for this portion of the site. The airflow velocity recorded at the vent stack decreased from a high of 18.5 m/s (at 55-mm Hg) to a low of 1 m/s (at full vacuum) at the end of the final step. The system started to extract groundwater at a wellhead vacuum of approximately 187.7-mm Hg. The liquid recovery rate could not be estimated during the step test because the pot filters were plugged soon after groundwater was recovered. The measured air velocity during the final step of the test was not accurate because the plugging of the pot filters. Prior to initiating the long-term test, the filters were removed.

Results of the Long-Term Test—During the test, the unit was extracting air from the subsurface at a flow rate ranging from 635 L/min to 2240 L/min with a system vacuum of 475–525-mm Hg. Once the dilution valves were completely shut, the vapor concentration in the effluent of the knockout drum was >100 percent LEL. This value remained constant for the duration of the test. The estimated petrol extraction rate varied

over the duration of the test from a high of 146 L/day at the beginning of the test to a low of 41 L/day at the end of the test. However, the extraction rate fluctuated during the test and did not simply attenuate over the testing period. The lower estimated extraction rate measured on the final day of the test was coincidental with a rise in the groundwater level within the extraction well, although the unit was extracting fluids at a higher flow rate than the day before. The lower airflow through the formation, the increased water flow rate, and the decrease in draw-down all may be attributed to the 25 mm/day of rainfall over the duration of the test. Using a vacuum response cut-off of 2.5 mm of water head in the observation wells, the radius of influence for the observed air flow rate and vacuum pressure was approximately 18–45 meters, depending on the lateral direction from the extraction well. This asymmetric shape of the area of influence is believed to be due to the lithological heterogeneity.

The draw-down in the extraction well during the test initially stabilized at 0.7 meters, decreased to approximately 0.6 meters after 6 hours and further decreased to 0.2–0.3 meters by the end of the test. The corresponding liquid flow rates were 20 L/min, 15 L/min, and 11 L/min and a slight increase to 16 L/min for the final day of the test. During pumping, liquid level drawdown was observed in five boreholes. Groundwater upwelling was measured in one borehole throughout the test and in two other boreholes at the very end of the test. Based on the maximum observed drawdown in the observation wells, it is estimated that the radius of influence was approximately 35 meters. The corresponding hydraulic conductivity, assuming a natural groundwater gradient of 0.03 was approximately 2.5–3 meters (distance to the down gradient stagnation point).

Cost Data—Not included.

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III. CHLORINATED SOLVENTS (DNAPLS)

Polyaromatic hydrocarbons (PAHs) range in solubility from somewhat soluble to not soluble. Some PAHs are solid at ambient temperature. Chlorinated solvents (also called chlorinated hydrocarbons) are hydrocarbons with one or more chlorine atoms. Most chlorinated solvents are also denser than water and thus are often referred to as dense non-aqueous phase liquids (DNAPLs). However, some DNAPLs are not chlorinated, and a few chlorinated solvents are less dense than water. DNAPLs and chlorinated solvents are sometimes referred to in the literature as being an equivalent group of chemicals. One should bear in mind that they are not quite the same. Chlorinated solvents were considered for many years to be recalcitrant to remediation. At present, natural attenuation in soils and groundwater and passive barrier walls for solvents in groundwater are the two field-ready technologies that are potentially of greater use because they are less expensive than other solvent cleanup methods. Dual-phase recovery followed by chlorinated solvent destruction at the surface is also a potential method, although it is more expensive.

Surfactant use of product recovery, hydraulic barriers with poplar trees, and enhanced remediation are other methods. Although not considered field ready, these technologies deserve mention because early results show they could be good cleanup methods. Planting poplar trees to prevent a chlorinated groundwater plume from moving further is inexpensive. Surfactant use and enhanced remediation may be more expensive because they both involve adding materials to the subsurface. Surfactant use requires the injection of a surfactant to help remove solvents attached to soil particles. The resulting surfactant-chlorinated solvent mixture is pumped to the surface for treatment.

Adding a carbon source to subsurface groundwater is known as enhanced remediation, and knowledgeable persons estimate that a field-ready technology will be available in 2001 or 2002. Co-metabolic processes are enhanced by the presence of an energy source for microorganisms, since chlorinated solvents are not used for this purpose.

Sometimes, regulators set groundwater cleanup standards to concentration-based standards for drinking water, but technologies to date have failed to meet those standards

because many factors were not considered when standards were set. Containment, instead of cleanup, and monitoring of the site while relying on natural attenuation are parts of the proposed risk-based approach.

A. CHLORINATED HYDROCARBONS (DNAPLS) CASE STUDIES

Soviet troops used 72 locations in the Czech Republic from 1968 to 1990. Contamination and damage was found at 60 of these locations. The overall amount of contaminated soil was estimated to be 1.24 million cubic meters (m³). Due to the need for massive groundwater pollution cleanup, immediate emergency cleanup pumping started at 54 sites. Contaminants included LNAPLs, DNAPLs, poly-chlorinated biphenyls (PCB), heavy metals, and other toxic substances.

Decontamination and cleanup started in 1991 and, at present, only 9 localities are still being cleaned up. The former military area at Ralsko (an area of about 250–300 km²)¹, which includes the former air base at Hradčany (Site 2 below), was the largest area used by the former Soviet Western Troops Group (WTG). One thousand tons of LNAPLs have been removed from this area. In order to reach the acceptable cleanup levels, about 4000–5000 tons of LNAPLs must still be removed. The decontamination should be complete in 2008.

The former Soviet military area of Mladá (area about 60 km²) is described in Site 1 below. The military air base Boží Dar at Mladá is polluted mainly by LNAPLs. Decontamination is expected to be complete in 2005.

All investigation and remediation work was paid by Czech state budgets. From 1990 to 1998, government costs for site investigation, decontamination, risk analyses, and supervision were about CK 890 million (about US\$ 29.5 million).² Only the most necessary remediation projects were addressed. Additional costs are expected to be about CK 400–450 million (US\$ 15 million) from 1999 until the expected completion date in 2008. Total costs for decontamination of groundwater and soil and removal of dumps are now estimated around CK 1.3–1.4 billion (US\$ 50 million).

¹ The Czech Republic is approximately 80,000 km².

² At 1998 rates of exchange.

1. Site 1—Environmental Restoration at Milovice-tábor (Milovice Training Ground), Czech Republic³

Contaminants—Hydrocarbons (LNAPLs), chlorinated hydrocarbons (DNAPLs) (their value is below cleanup limits), and halon contamination reaches 30 meters deep in the unsaturated zone. Although data on location of the LNAPLs and DNAPLs were unavailable, such contaminants migrate to different locations and depths, depending on the density of each compound and the local geology.

Media—Parent rock, sandy limestone, silt, limestone, limy clay, and cretaceous sediments. Grain is larger with depth. In the deeper parent material, non-permeable lime desks (banks) exist, but tectonic lines and open fissures (rifts) are often very long. The Mlynařice River Valley is surrounded by quaternary blow sediments (2–3 meters thick) and alluvial sediments 8–9 meters thick at average (sometimes 15–20 meters thick).

Coefficient of hydrological permeability is 10^{-4} – 10^{-5} , but there is good percolation through fissures. Groundwater level is 3 (the river Mlynařice basin) to 41 meters (large-scale oil storage) deep.

Threat—Contaminant poses threat to groundwater and local drinking water sources (wells). Migration into the Mlynařice River has been stopped by a hydrological shield.

Restoration Technology—Different strategies are used at different facilities:

- Large-Scale Oil Storage—Biodegradation *ex situ*, groundwater pumping with protective depression (8–10 liters/second of contaminated water has been pumped), venting.
- Siding and Manipulation Tanks (20 tanks, each holding, 20,000 liters) with Heavy Contamination—Biodegradation, surfactant usage, free phase pumping.
- Garages (Autoparks 1, 2, and 3)—Biodegradation, surfactant usage, free phase pumping, groundwater pumping (11 liters/second of contaminated water has been pumped), venting. Recycling of the asphalt surface areas and roads. Removal of buildings and washing bridges.
- South Gate—Hydraulic barrier at the Mlynařice River, demolition of building, biodegradation *ex situ*, groundwater pumping (5–10 liters/second of contaminated water has been pumped). Halons will be pumped out of the pipes remaining after computer central installation.

³ This site is included in fuel hydrocarbons section also.

Location—Central Bohemia, 30 km north of Prague, this site is a part of the former Soviet military area of Mladá (area ca 58 km²) on the south border (Milovice Training Ground or Milovice town).

Description—The size of the city area is about 4 km². Five contaminated sites are mentioned: oil storage (LNAPLs, DNAPLs), three garages (LNAPLs), and a building near the south gate (DNAPLs in the former clothes-cleaning building and halons in the computer center building)

History—This area has been a military base since the time of the Austrian Empire. It was also used for military purposes after the Czechoslovak Republic was established in 1918 and during the German occupation until 1945. After WWII the Army of the Czechoslovak Republic used it again. From 1968 to 1992, the Soviet Union occupied it. Some of the contamination has been here since the Austrian Empire, while some massive contamination occurred in World War II. Investigation and cleanup started in 1989 (two companies carried out most of the work: Aquatest Prague until spring 1996, then Top Eko Příbram from 1996 to 1998). From April 1997 to August 1998, only monitoring was needed, and since September 1998, a groundwater protection company, OPV Ltd., has been working there. OPV intends to finish the cleaning up of the entire camp in 2005 and then to continue with monitoring for 2 more years. About 2000 cubic meters (m³) of soil have been excavated. The hydrocarbon contamination varies from 100 mg/kg soil to 10,000 mg/kg soil (maximum concentration of contaminants reaches 38,000 mg/kg of dry soil).

The total amount of contamination is not recorded. Specifics about success of treatment and post-treatment levels of contamination were not included with this case study.

Cleanup Standard Limits—LNAPLs: 1500 mg non-extractable substances (NES)/kg of dry soil and 5 mg/liter; DNAPLs: 120 micrograms (µg)/liter of groundwater and 20 µg/m³ in soil air.

Costs

- August 1998 to 2007: CK 86 million (US\$ 2.7 million), for the OPV Company only
- May 1997 to August 1998: Monitoring only: CK 13 million (US\$ 410,100)
- April 1996 to May 1997: CK 35 million (US\$ 1.1 million) (Top Eko Příbram totals CK 47.94 million)

Cleanup from 1994 to 1996 (Aquatest budget):

- 1996: CK 2 million (US\$ 74,074)
- 1995: CK 30 million (US\$ 1.13 million)
- 1994: CK 6 million (US\$ 208,333)
- Years prior to 1994: approximately CK 0.8–1.5 million per year.

Remarks

1. Be alert to the exchange rate of Czech Koruna (CK) to US Dollars (US\$), and be aware of inflation. The CK has experienced dramatic price inflation from 1994-1999.
2. The Ministry of Environment paid for these locations where investigation and restoration began, but no comprehensive data are available.
3. available.

2. Site 2—Former Air Base Hradčany, Czech Republic⁴

Contaminants—LNAPLs, DNAPLs

Media—Saturated zone, non-saturated zone.

Threats—To the Ploučnice River and sources of underground drinking water.

Restoration Technology—Cleanup pumping, venting, bioventing, air sparging.

Location—The village of Ralsko in the north of Bohemia (approximately 80 km from Prague) and near the German border at Zittan.

Description—Former military air base with POL supply infrastructure (tanks, pipes, siding, pumps, hydrants, and delivery points), workshops, army barracks, and accommodation for soldiers and families.

History of the Site—It was a former military area of the Czech Armed Forces and of the Former Soviet Union from 1968 to 1992.

Area of Contamination—Area ranging to hundreds of hectares.

A Specific Case at Air Base Hradčany—*In-situ* remediation of soil and groundwater polluted by jet fuel on the former Air Base Hradčany, Czech Republic.

Site Characteristics—The former Hradčany military air base is located in Northern Bohemia, near the district town Ceska Lipa. Nazi Germany built the air base in 1944; it was used by the Soviets from 1968 to 1990. The air base and its vicinity are in

⁴ This site is included in fuel hydrocarbons section also.

the sedimentary complex of the Bohemian Cretaceous Basin, which forms the main groundwater supply of the Czech Republic. Pollution of soil and groundwater by jet fuel is spread in the alluvial sediments of Ploučnice River and in the Middle Turonian sandstones.

The Middle Turonian unconfined aquifer reaches an average thickness of 70 meters. The aquifer permeability is of the fissure-porous type, hydraulic conductivity averages at 8 meters/day, reaching up to 30 meters/day in the upper part of the aquifer. Groundwater level is 4–6 meters below the surface in the polluted areas. Annual groundwater level fluctuation varies between 0.3–0.7 meters in the area of interest.

Groundwater of the Middle Turonian aquifer flows through the contaminated area of the air base towards the Ploučnice River. Water quality is endangered by seepage of groundwater polluted by oil hydrocarbons. A water works (with capacity 35 liters/second), drawing from the Middle Turonian aquifer, is located near the air base. The wellhead protection area partly overlaps the area of groundwater pollution based on the results of groundwater modeling. The pumped amount was reduced to prevent the polluted water from entering the well field area.

Soil and Groundwater Pollution—According to the results of gas chromatography/mass spectrometry (GC/MS) analysis, the pollutants were jet fuel, 66.0 percent; diesel oil, 19.5 percent; petrol, 8.0 percent; fuel oil, 6.0 percent; and chlorinated solvents, 0.5 percent.

Operational leakage during the past 40-year period has resulted in mixed contamination concentrated in soil around groundwater level fluctuation. The smear zone averages 1.2 meters below the current groundwater level. The total contaminated thickness with the smear zone averaged 1.7 meters.

The entire soil profile is contaminated in storage areas, where tanks with jet fuel were stored on sandy soils without any protection. The thickness of free oil product at the very beginning of remediation in 1989 reached maximum 6 meters, and the median or common thickness varied from 5 to 80 cm in storage areas.

The heavily polluted area of soil and groundwater (exceeding cleanup limits) covers about 17 hectares. The volume of contaminated soil was estimated at 290,000 m³, while the total quantity of oil hydrocarbons in soil was estimated at 5400 tons.

The cleanup limits given by the Czech Ministry of Environment, based on the results of risk analysis, were as follows:

- Oil hydrocarbons in soil = 5000 mg/kg
- Oil hydrocarbons in groundwater = 5 mg/L
- BTEX in groundwater = 1000 µg/L
- Chlorinated solvents = 1000 µg/L.

Remediation—Remediation started in 1989. The most heavily polluted areas had between 24 and 32 boreholes placed in them. Water was pumped, then treated in gravitational separators and finally in a sewage water treatment plant. This two-step treatment approach enabled the pumping of relatively large amounts of groundwater (25 liters/second), as well as meeting the cleanup standards of oil hydrocarbon content (0.5 mg/liter) before return to the river.

In 1993, a bioventing method was implemented over a 3.5-hectare area. This bioventing field operated successfully over a 3-year period. Venting wells were located in regularly spaced networks either 10 x 10 meters or 15 x 15 meters in accordance with the results of soil gas permeability tests.

When the pump-and-treat method decreased in efficiency in 1996, a dual-phase extraction was implemented. This method enabled suction of free phase from venting wells, which were equipped with a screen 2 meters below the groundwater level.

Controlled aerobic bioremediation efforts started in 1996. A bacteriological screening of soil and groundwater found that relatively high densities of soil bacteria were present in polluted areas that degraded the fuels. Laboratory tests indicated that more rapid bacterial growth would occur if nutrients were added (nitrogen, phosphorus, potassium). Growth was 5–10 times more in comparison to control samples. The proper composition of nutrients was then tested in the laboratory. In the field, respiration tests and venting monitoring determined the proper composition of nutrients in the bioventing fields.

A crucial condition for aerobic biodegradation is a sufficient supply of oxygen. Two systems are used for oxygen delivery: venting and air sparging, using ambient air to bring in oxygen. The venting method could not address the most polluted part of soil profile around the smear zone (the water table fluctuation). For this reason, air sparging was implemented to promote bacterial activity.

In 1996, air-sparging wells were drilled in networks of 15 x 15 meters. The height of the water column was determined to be 6 meters. The increased concentration of oxygen in groundwater was measured and was considered the most important effect of air sparging.

Agricultural fertilizers were added through the venting pipes. Nutrient addition showed positive results after 6 months. The distribution of fertilizers in groundwater was very irregular in the first year. After the second year of application, the distribution of concentration of fertilizer was more even, and biodegradation rates increased. During the first year of controlled bioremediation (venting + air sparging + nutrient addition), the average biodegradation rate reached 2 mg/kg/day. During the second year, the average biodegradation rate was 5 mg/kg/day. Biodegradation activity was monitored by measurements of concentrations of respiration gases in the venting system (for total biodegraded amount) and by conducting *in situ* respiration tests using respiration probes at specific points.

In 1999, a controlled bioremediation was implemented in a 10-hectare area and bioventing and dual phase extraction on 5.1 hectares. The total remediated area was 15.1 hectares, with 950 bioventing wells (25 blowers, each at 180 m³/hour), 650 air-sparging wells (8 compressors, each at 100 m³/hour), and 180 dual suction wells (9 vacuum pumps, each at 80 m³/hour). Groundwater was pumped from 12 wells with total discharge 4.5 liters/second. This effort was ongoing through the end of 1999.

Remediation Results—The pump and treat method was relatively successful over a long period (1989–1996), due to the large amount of free product. After a time, however, the output of oil hydrocarbons from pumping wells decreased, so dual phase pumping on bioventing fields was implemented (see Table 4 below). After 1997, controlled bioremediation has become the most successful method of remediation, promising results that can meet the relatively high cleanup limits.

Table 4. Results of the Groundwater and Soil Cleanup on the Hradčany Airport (1989-1999)

Units are in metric tons (1 ton = 1000 kg) of mixture of fuels or oil hydrocarbons

Methods	Years								Total
	1989–1992	1993	1994	1995	1996	1997	1998	1999	
Water Pumping ^a	238	23	52	79	45	52	35	31	555
Venting		2	7	36	34	7	32	11	129
Bioremediation			18	43	86	109	131	191	578
Grand Total	238	25	77	158	165	168	198	233	1262

^a Dual phase extraction is included in water pumping balance from 1996.

The cleanup of the Hradčany airport is planned to continue through 2008. Areas where the oil pollution exceeded cleanup limits are divided into remediation fields (0.5–4

hectares each). Remediation of a field is projected to last approximately 6 years. Monitoring of residual pollution will start once cleanup limits are achieved.

The Czech Ministry of Environment funded the remediation. The final stage of remediation is planned for the period from 1997 to 2008. The total planned costs of proposed remediation are CK 344 million.

3. Site 3—Milovice Air Base Boží Dar, Czech Republic⁵

Contaminant—LNAPLs (jet fuel, diesel, engine oil), DNAPLs (trichloroethene, tetrachloroethene).

Media—Saturated zone, non-saturated zone.

Geology—This is the Bohemian Cretaceous Basin, with sandy limestone and siltstones with deep weathering about 3–4 meters (sandy clay soils), and residual quaternary terrace sediments (sandy gravel soils) some meters thick.

Hydrogeology—The groundwater level of the first Cretaceous aquifer is 5–8 meters deep. The groundwater flow is generally south, but the local groundwater flow varies depending on permeable fractures.

Threat—To sources of drinking groundwater, especially individual groundwater wells in the nearby village of Zbozicko, and to surface water. Nearby creeks of Vlkava (to the east) and Mlýnařice, on the southern edge of the air base, are threatened.

Restoration Technology—Removal of buildings, pump and treat, venting, and biodegradation. Thousands of cubic meters of contaminated soils were remediated by biodegradation. Hundreds of thousands of cubic meters of contaminated groundwater were pumped out beginning in 1991. Several hundred tons of LNAPLs and several hundred kilograms of chlorinated hydrocarbons have been removed.

Location—Central Bohemia, 30 km north of Prague, part of former Soviet military area of Mladá (area about 58 km²) at the south border (Milovice Training Ground or Milovice town).

Description—Former military air base with POL supply infrastructure (tanks, pipes, and pipeline), garages, workshops, stores, chemical cleaning facilities, army barracks, accommodation for soldiers and families.

⁵ This site is included in fuel hydrocarbons section also.

Area of Contamination—About 10 percent of the whole area, which is about 10 km², was contaminated to a depth about 20 meters.

History of Site—This area was a military base since the time of the Austrian Empire. It was used for military purposes after the Czechoslovak Republic was established in 1918 and during the German occupation. After the German occupation, it was used again by the army of the Czechoslovak Republic to 1968, and by the Soviet Union from 1968 to 1992.

4. Site 4—Olomouc-Neředín, Czech Republic⁶

Contaminant—LNAPLs, DNAPLs

Media—Saturated zone, non-saturated zone

Threat—To local sources of underground drinking water (private wells)

Restoration Technology—Removing of buildings, cleanup pumping, venting.

Location—Olomouc city in central Moravia (about 240 km east of Prague).

Description—Former military helicopter base with workshop and maintenance, garage, army barracks, and POL facility.

Area of Contamination—Hundreds of hectares.

History of Site—Former military army barracks used from 1968 until 1992 by Western Troops Group.

Cleanup Standard Limits—Not included.

Costs—Not included.

5. Site 5—Zákupy, Czech Republic

Contaminant—LNAPLs (light petroleum and aromatic hydrocarbons)

Media—Saturated zone, non-saturated zone.

Geology—Bohemian Cretaceous Basin, Turonian thick-bedded sandstones, with deep weathering about 2 meters of sands: fluvial bed sorted sediments around the Svitávka creek about 6 meters thick (gravel-sand-silt-clay sediments in a wide marshy flood plain).

⁶ This site is included in fuel hydrocarbons section also.

Hydrogeology—The groundwater level of the first Cretaceous aquifer is 2–4 meters below the surface. The groundwater flow is in the direction of the Svitávka creek, about 50 meters west. Permeability is mostly in pores near the surface, and partly in fractures below the surface.

Threat—To collectors of drinking water with regional sources and the brook Svitávka.

Restoration Technology—*Ex situ* biodegradation, venting, cleanup pumping.

Location—The village of Nové Zákupy, near Kuřivody.

Description—Former POL storage in the sandstone quarry.

Area of Contamination—About 1 hectare.

History of Site—POL storage was started by the Soviets in the 1970s.

Cleanup Standard Limits—Not included.

Costs—Not included.

6. Site 6—Jirice (in the District of Mladá Boleslav) Central Bohemia⁷

Location—The Jirice site is situated to the north of Prague on the left bank of the Jizera River near the towns of Benátky and Jizerou.

Contaminant—The presence of underground oil is connected with the handling and storage of liquid fuels. Hot spots of groundwater and vadose zone contamination with chlorinated hydrocarbons exist, probably resulting from dumping of used chlorinated solvents. The source of local high zinc concentrations in the groundwater may be from the use of ammunition on the nearby firing range.

Chlorinated aliphatic hydrocarbons [trichloroethylene (TCE), perchloroethylene (PCE)] were the main contaminants at this site, exceeding general Czech limits “C” for CHC in groundwater (e.g., TCE 50 µg/L, PCE 10 µg/L). They were accompanied with oil hydrocarbons and aromatics in lower concentrations in groundwater, but in significant concentrations in soil air as well.

Contamination of groundwater with zinc exceeding limit “C” (5 mg/L) was also observed (maximum 2200 mg Zn/L) but only in a few wells. This zinc contamination

⁷ This site is included in fuel hydrocarbons section also.

Contamination of groundwater with zinc exceeding limit "C" (5 mg/L) was also observed (maximum 2200 mg Zn/L) but only in a few wells. This zinc contamination had no causal connection with oil hydrocarbons and/or chlorinated hydrocarbons in the aquifer.

Media—From a geological point-of-view, the subsurface is predominantly fractured, with tectonic faults and crevices that also affect groundwater flow and contaminant migration. The groundwater table lies between 20–35 meters below ground level. The site is situated in the vicinity of a hydrogeological water shed divide.

Threat—The hydraulic gradient declines to the Jizera River valley where wells of the regional Káraný waterworks are situated. The distance between these wells and the contaminated area is about 3 km. The Jirice site lies within an outer protective zone of the Jizera River.

History of Site—It was a part of a vast military training area called Mladá that was occupied by the Soviet Army in August 1968. This area was not inspected until 1990, when discussions about the Soviet troop withdrawal began. (Comment from the contributor of this case study: "The following data on land use may not be reliable.") Contamination was greatest at the so-called Camp No. 19 (800 x 900 meters), where there was a parking lot for trucks and combat vehicles, workshops, and fuel storage with 20 underground tanks for diesel and petrol with a total volume of 1240 m³. A mobile laundry also may have been present. A large firing range (750 x 500 meters) was situated close to Camp No. 19.

Restoration Technology—The decrease of chlorinated hydrocarbon concentrations in cleanup wells during remediation of groundwater is shown in Table 5. The following local limits were set for groundwater: benzene, 10 µg/L; toluene, 1000 µg/L; PCE, 10 µg/L; total CHC, 30 µg/L. These limits changed when it was decided that the area under remediation would be used as an industrial zone with the existing drinking water supply from the external municipal waterworks. The on-site limits of chlorinated hydrocarbons then were made in accordance with the calculated off-site risks as follows: PCE, 100 µg/L; total CHC, 300 µg/L.

Soil gas in the deeper part of the unsaturated zone (5–30 meters) at the very beginning of cleanup contained hundreds of mg/m³ of oil hydrocarbons (up to 760 mg/m³), high concentrations of aromatics, mostly toluene (up to 478 mg/m³) and tens to hundreds of mg/m³ of chlorinated hydrocarbons (up to 390 mg/m³), mostly PCE followed

by TCE. Daughter products such as dichloroethane, dichloroethylene, tetrachloromethane, and chloroform were found at much lower concentrations.

Table 5. Average Concentration of Chlorinated Hydrocarbons in Groundwater at Jirice Site

Remediation Well	Chlorinated Hydrocarbons in $\mu\text{g/L}$					
	1993	1994	1995	1996	1997	1998
HJ 2	441	482	387	177	89	84
HV 11	172	225	99	36	9	7
HV 12	158	207	137	97	66	73
HV 15	246	206	155	9	16	23

The following local limits for soil air were set for the depth of 1 meter below ground: toluene, 70 mg/m^3 ; and total CHC, 6.5 mg/m^3 . During remediation, oil hydrocarbons disappeared completely and the content of chlorinated hydrocarbons was at least halved; 75 percent of the venting boreholes became practically clean. (The process yielding this result was not included in this case study.) Only one well contained high concentrations of CHC (100 mg/m^3 at the maximum) and this occurred in the deep part of the unsaturated zone. The shallow part of unsaturated zone (0–2 meters) contained concentrations one order of magnitude smaller both for HC and CHC vapors at the beginning of soil vapor extraction (SVE), and at the end of remediation the concentrations of oil and chlorinated hydrocarbons declined to near zero.

Remediation of groundwater was based on pumping and treating from 5 to 8 wells. There were three aims of pumping: to create protective hydraulic depressions; to remove the contaminants from the aquifer; and to extend the thickness of the unsaturated zone in the vicinity of the capillary fringe for the intensification of the SVE. The total yield of pumped water varied from 5 to 12 liters/second depending on the climatic conditions. The remediation started in 1993 and was finished in 1998. Pumped water was treated by air stripping in three towers. To enlarge the water/air interface, the tower was filled with loose plastic fillings. After stripping, the air was cleaned through activated carbon filters that were recharged on-site with the help of steam. Condensed chlorinated solvents were burned off-site. The cleaned water was recharged totally on the outskirts of the contaminated plume either via sprinklers on the ground surface or by injection into infiltration wells. In the second case, water was treated on the two stripping towers in series. During remediation, 2 kg of oil hydrocarbons and 249 kg of chlorinated hydrocarbons (mostly PCE and TCE) were removed. Water containing high concentrations of zinc was pre-treated with the help of a zeolite filter.

Remediation of the unsaturated zone was based on SVE, air injection, and its intensification by well blasting. There were two venting fields consisting of 5 extraction wells, each finished above groundwater level at depths of 15–30 meters. Four deep wells for remedial pumping (with depth to 40 meters) were situated at the point of massive contamination and the conducting fractures throughout the site. These four wells were later incorporated into the SVE system.

The SVE system consisted of three vacuum pumps (capacity of 60 liters/second) and one vacuum pump (capacity of 30 liters/second). One pressure blower (capacity of 50 liters/second) was used for air injection into relatively clean wells on the outskirts of the contaminated area to accelerate decontamination processes. The vapor treatment system consisted of a dehumidifier unit and active carbon filters; during hot weather, this included a cooler. The SVE system operated from February 1995 to December 1998. Extraction wells were switched on and off according to the actual level of CHC concentrations. The respective system was shut off when CHC concentrations declined repeatedly below standards (individual CHC 10 mg/m³), or when the removal rate was lower than 5 kg of volatile contaminant per month. The exception was one permanently contaminated well where remediation was ended when the local limits were reached for groundwater and the uppermost part of unsaturated zone.

When a very low contaminant flux occurred, well blasting was successively employed as shown in Table 6.

Table 6. Effect of Well Blasting on Hydrocarbon Concentrations in Soil Air During Experimental Soil Vapor Extraction (12 liters/second) at Jirice Site

Well	Under Pressure Caused by SVE Before Blasting (kPa)	HC Content in Soil Air Before Blasting (mg/m ³)	Under Pressure Caused by SVE After Blasting (kPa)	HC Content in Soil Air After Blasting (mg/m ³)
Ji 1703	6.2	0.0	3.2	220
V 1709	14.5	0.0	1.2	350
V 1714	14.0	0.0	4.2	60
V 1717	14.5	350.0	8.0	1000
V 1712	12.5	220.0	9.0	3600

kPa = kilopascal

Soil vapor extraction removed 285 kg of oil hydrocarbons and 1610 kg of chlorinated aliphatic hydrocarbons. Another 5000–10,000 kg of oil hydrocarbons were estimated to be decomposed by microbial activity during SVE and air injection, according to a rise of CO₂ content in the exhausted soil air and its comparison with the soil air in clean parts of the unsaturated zone.

Cost—The total cost of groundwater remediation, including quality monitoring, was CK 9.2 million (US\$ 2.7 million). The total cost of soil vapor extraction was CK 4669 million (US\$ 154,600).

Documentation

1. Svoma, J., *Cleanup of Jirice Site and Emergency Self-guarding Pumping at the Mladá Military Base Between Jirice and Vsejany Sites: Final Report*, M. S. Aquatest SG Praha, Ministry of Environment Praha, Czech Republic, May 1999. (In Czech)
2. Svoma, J., Kroova, H., *Experience with Remediation Investigation and Research of Contaminated Sites in the Czech Republic*. "Draft for Tour de Table" Presentation for Phase III NATO/CCMSD Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment and Cleanup of Contaminated Land and Groundwater. Held at the Hotel Bleu Marine, Angers, France, 9-14 May 1999.

7. Site 7—Hvezdov, Northern Bohemia⁸

Contaminants—LNAPLs (hydrocarbons: petrol, diesel oil, engine oil, heating oil), DNAPLs (tetrachloromethane).

Contaminant Sources—LNAPLs came from motor pools, vehicle repair sites, oil storage, boiler houses, and coal stocks (dangerous liquid pollutants were poured out into coal stocks and then burned up—unfortunately a significant part of the pollutants infiltrated into subsoil), oil transformers, and petrol stations. The DNAPLs emanated from the extinguishing medium in military rocket launchers.

Media—Soil and subsoil.

Geology—Bohemian Cretaceous Basin, Turonian thick-bedded sandstones, deep weathering of about 6 meters creating sandy soils, 4- to 6-meter-thick fluvial bed sorted sediments around small creeks with gravel-sand-silt-clay sediments.

Hydrogeology—The groundwater level of the first Cretaceous aquifer is 4–10 meters. The groundwater flow is in the direction of local creeks.

Threat—The threat to a very important regional aquifer used for drinking water and a significant waterworks. The Plouznicky Potok creek is a stream used as drinking water, but its drainage basin includes contaminated groundwater. The original water

⁸ This site is included in fuel hydrocarbons section also.

wells that supplied Hvezdov were threatened too, but because people did not live in Hvezdov in the 1990s, that water supply was not used. A new water supply for new settlers now comes from the nearby town of Mimon.

Restoration Technology—*Unsaturated zone.* Soils with LNAPL concentrations over cleanup limits were removed from the site and biodegraded in special biodegradation fields.

Soil vapor extraction methods removed significant amounts of volatile aromatic and chlorinated hydrocarbons from contaminated soils.

Saturated zone. Groundwater pumping, followed by stripping and filtration, intercepted the contaminant plume. There were two main pumping centers: Hvezdov I, pumping about 3–5 liters/second of contaminated water with only LNAPLs, and Hvezdov II, pumping about 10 liters/second of both LNAPLs and DNAPLs. The groundwater pumping had functioned as a hydraulic barrier to help protect the water quality in creeks.

Location—The site Hvezdov is in northern Bohemia, about 80 km from Prague, near the town of Mimon, between other Soviet military sites (Hradčany 2 km, and Zákupy 8 km). The site has an area of about 15 km².

Description—This site was a former Soviet military rocket base from 1968 to 1990. Previously, it was an agricultural and forest area.

Amount of Contamination—About 4 percent of the area was contaminated to a depth of about 20 meters. Approximately 10,000 m³ of contaminated soils were remediated by biodegradation methods. About 500,000 m³ of contaminated groundwater was pumped out between 1991-1995, when the remediation was completed. Approximately 400 kg of trichloromethane were removed, and about 50 tons of LNAPLs. The residual concentrations at the completion of remediation were: soils, 1000 mg/kg of LNAPLs; groundwater, 5 mg/L LNAPLs; groundwater, 100 µg/L of trichloroethane.

Costs

- 1990-1991: Site investigation: CK 3.7 million (US\$ 125,000), total cost.
- 1991-1995: About CK 25.9 million (US\$ 977,000) total.
- The original budget for remediation was estimated to be larger, and strict cleanup levels were set (analogous to drinking water quality) but not reached. Because of the lack of money in the state budget, remediation efforts were completed in 1995, though originally planned to run to 1997. Most contaminants were removed or remediated.

8. Site 8—Lustenice, Central Bohemia⁹

Contaminants—LNAPLs (hydrocarbons: petrol, diesel oil, engine oil, heating oil), DNAPLs [tetrachloroethene (perchloroethene, PCE) and trichloroethene, TCE].

Contaminant Sources—LNAPLs from motor pools, vehicle repair sites, oil storage, oil transformers, petrol stations; DNAPLs from chemical cleaning and laundry facility.

Media—Soil and groundwater.

Geology—Bohemian Cretaceous Basin, Turonian marlites, sandy marlites, siltstones, with deep weathering about 3–4 meters (sandy clay soils), and fluvial bed sorted sediments 2–3 meters thick around the Struzsky Potok creek (gravel-sand-silt-clay alluvial sediments).

Hydrogeology—The groundwater level of the first Cretaceous aquifer varies from 3–20 meters below the surface. The groundwater flow is in the general direction of the Jizera River (about 2 km to SW), but the local groundwater flows vary due to permeable fractures in the subsurface.

Threat—Groundwater flows into the Jizera River. Surface water and groundwater pumped from the Jizera River fluvial sediments (including artificial recharge facilities) are used as drinking water for Prague. The waterworks of Káraný have a capacity of 120 liters/second.

The original Soviet water wells for a former water supply in Lustenice were threatened, but people did not live there in the 1990s. A new water supply for new settlers comes from the nearby waterworks of Káraný. The Struzsky Potok creek was heavily contaminated by LNAPLs and DNAPLs (both surface water and stream sediments), which supplied individual wells in the nearby village of Struhy, about 1 km away.

Restoration Technology—*Unsaturated zone.* Soils with LNAPLs over cleanup limits were removed from the environment and biodegraded on site in special biodegradation fields. Soils with a significant amount of both aromatic and chlorinated volatiles around the former laundry area were remediated by soil vapor extraction.

Saturated zone. Groundwater pumping was used in the contaminant plume in four places. First, the chemical laundry, which pumped about 3–5 liters/second of

⁹ This site is included in fuel hydrocarbons section also.

contaminated water (LNAPLs and DNAPLs); second and third, two military auto parks together pumped about 2–3 liters/second (LNAPLs); and fourth, a transmitter center, which pumps about 1 liter/second (heating oils). Filtration decontaminated the water at all four locations. The laundry area water was also air stripped and groundwater pumping created a radial hydraulic barrier to help protect the water quality in the civilian neighborhood.

Location—Lustenice is near the towns of Benátky and Jizerou in central Bohemia, about 30 km north of Prague, and near other former Soviet military sites (Milovice, Jirice and Boží Dar, all to the south). The site is about 17 km² in area.

Description—This site was a longtime military base: Austrian (before 1918), Czech (1918–1939), German (1939–1945), Czech again (1945–1968), and Soviet (1968–1990). As of 1991, the area is non-military. An industrial zone is planned here and much of the surrounding area will remain as forests.

Amount of Contamination—About 20 percent, or 3.5 km², of the 17 km² total area was contaminated to a depth about 30 meters. Approximately 10,000 m³ of contaminated soils were remediated by biodegradation methods. About 1,200,000 m³ of contaminated groundwater was pumped out from 1991–1995, when the remediation was completed. About 5 tons of chlorinated hydrocarbons and 100 tons LNAPLs were removed. The residual concentrations after completion of remediation were: soils, 500 mg/kg LNAPLs; groundwater, 5 mg/L LNAPLs; groundwater, 100 µg/L DNAPLs.

Costs

- 1990-1991 (site survey stage): US\$ 300,000
- 1991-1995: About US\$ 1.4 million

The original budget for remediation was estimated to be larger, and strict cleanup levels were set (analogous to drinking water quality) but not reached. Because of the lack of money in the state budget, remediation efforts ended in 1995. Most contaminants were removed from the site.

9. Site 9—Canadian Forces Base Goose Bay, Canada: PCB-Materials Incineration Project

The Department of National Defence embarked on the first successful use of mobile PCB incineration in Canada in 1989 at the CFB Goose Bay facility, 200 km inland from the Labrador Sea coast. A total of approximately 3500 metric tonnes of PCB contaminated materials were treated using a mobile infrared incinerator, including mostly

soils from the cleanup of transformer spills at radar sites in Labrador abandoned in the 1970s and 1980s. These soils were stored in drums at some former radar sites in the north and were transported to Goose Bay for treatment. Along with the soils were other materials such as transformer bodies, containers, wood products and other materials that exceeded the prescribed definition of a hazardous waste (50 ppm) and therefore required treatment. A steering committee, formed at the outset of the project (with the major stakeholders being DND, Environment Canada, Newfoundland Department of Environment and Lands, and representatives from the Town of Happy Valley-Goose Bay), selected the incineration option. The steering committee was responsible for finding a way to destroy PCB material inventories at CFB Goose Bay in a safe, cost-effective manner.

Remote sites such as Goose Bay present unique challenges to conventional remediation strategies. Given the poor weather conditions, the only access for heavy equipment into Goose Bay is by sea. Because of ocean freezing, access is limited to 4 months: from mid-June to late October. All treatment equipment (incinerator and ancillary equipment, heavy machinery, etc.) as well as material to be treated was successfully transported to the site during this narrow window of time. An incineration structure was built to house all process operations in accordance with Canadian regulations and steering committee requirements.

The contractor's Mobile Infrared Incinerator is similar to other thermal destruction technologies except that it uses infrared energy as the heat source for the primary chamber. Four diesel fuel burners mounted on the forward end of the chamber fire the secondary chamber.

Before introducing any material into the primary chamber, the waste stream had to be prepared. All materials were passed through a crusher, except metals, plastics, and wood, which were removed before and during the process to avoid problems with the crusher. The wood, metal, and plastic materials recovered and diverted from the crusher were reduced to particle size of less than 2.5 cm by hydraulic shears in the shredder. Following crushing and shredding, the materials were blended with BTU enhancers (fuel) such as PCB oil and fuel oil in a pugmill prior to incineration. The pugmill also metered the feed rate and the BTU value to remain below the 5 tons/hour and 20,000 ppm limit.

After this preparation, the soil was loaded into a feed hopper using a front-end loader, where it was subsequently weighed and placed on the feed conveyor. The conveyor carried the material to a leveling system mounted directly over the incinerator,

which then fed the metered materials into the incinerator. Temperatures of approximately 1000 °C were developed within the primary chamber using infrared energy (sufficient heat to vaporize the organic contaminants from the solid matrix). The infrared energy was produced by way of transversely mounted silicon-carbide resistance heating elements. The material on the metal alloy belt was exposed to these heating elements in multiple-temperature control zones. The material was also stirred at several points in the furnace by means of cake breakers and exposed to combustion air provided by a draft blower that forced air in the opposite direction of the material flow. Air was also added at several other points in the furnace to promote maximum combustion and/or vaporization from the waste material and to provide proper turbulence in the chamber. A negative pressure is also induced in the furnace to prevent gas emissions.

The contaminated gases were then redirected through the secondary chamber. Four diesel fuel burners produced a temperature of 1200 °C and destroyed any remaining organic molecules. The exiting gases were then cooled with the help of quench water before entering a packed tower scrubber. This scrubber removed the remaining particulate matter, hydrochloric acid, and sulfur dioxide from the exhaust gases.

Two incinerator malfunctions caused significant delays in the project schedule. A power failure shut down the system's main draft fan about 3 weeks after the project began. An activating mechanism in the duct carrying the exhaust gases from the emergency backup fan blocked the duct and prevented discharge to the stack. Pressure built up in the primary chamber, causing subsequent release of small quantities of PCBs and products of incomplete combustion, PCDF and PCDD. The problem was rectified within 3 minutes. However, the follow-up response from DND and other stakeholders delayed the re-start for nearly a month. The building was extensively decontaminated, and an impartial technical team, who identified the cause and recommended changes that were adopted before restarting the unit, conducted a detailed investigation. Most importantly, the investigation found that workers were not exposed to dangerous levels of PCBs and/or PCDFs and PCDDs.

The second incident occurred in April when a second power failure caused the emergency back-up exhaust gas cooling system to fail. Because the quenching system did not cool the exhaust, the hot gases damaged the scrubber unit and smoke was released inside the building. Environmental consequences did not occur, but the reliability of the incinerator's exhaust system was compromised. The investigation team issued another full report with recommendations and re-start preconditions. After meeting all terms, incineration re-started 45 days from shutdown.

For the total 3500 metric tonnes of material collected, the minimal standard of treatment achieved was a Destruction and Removal Efficiency (DRE) of 99.9999 percent for soils.

Cost Data—Not included.

10. Site 10—Canadian Forces Base Cold Lake: Low Temperature Thermal Desorption of Fuel Hydrocarbon and Chlorinated Solvents Contaminated Soil¹⁰

In March and April 1998, approximately 9300 metric tonnes of contaminated soil were remediated at the Canadian Forces military base in Cold Lake, Alberta. The soil was contaminated with petroleum hydrocarbons, ethylene glycol, trichloroethylene, and phenol, stockpiled in various locations. The soil was treated with a mobile Low Temperature Thermal Desorption (LTTD) technology near one of the stockpiles. The system operated on a 24-hour-per-day schedule without disturbance to surrounding military operations. The LTTD operations occurred within 300 meters of the main aircraft runway used by military fighter jets and transport planes.

Samples of the treated soil were sent to an independent laboratory for analysis to confirm that the LTTD technology was remediating the soil to below the regulated criteria. The laboratory results indicated that all samples were below alluvial levels. Alberta Environment guidelines, Canadian Council of Ministers' of the Environment protocols, and Environment Canada's Technical Assistance Bulletins were adhered to throughout the project.

The contractor performing remediation was responsible for all soil remediation activities at the site, including screening and sorting stockpiled material, treating contaminated soil, and disposing of screened material. When LTTD operations were completed, the site was restored to user specifications, including grading the affected areas.

Cost Data—Not included.

¹⁰ This site is included in the fuel hydrocarbon section as well.

B. TECHNOLOGY DEVELOPMENTS, PILOT SCALE STUDIES

1. Site 1—University of Waterloo Pilot Scale Study Using an Iron-Based Catalyst

In 1993 the University of Waterloo conducted pilot scale research¹¹ involving the use of granular iron acting as a reactive catalyst (through corrosion) to degrade chlorinated solvents present in a groundwater plume.

As a controlled experiment, a plume was created containing approximately 250,000 µg/L TCE and 43,000 µg/L PCE (tetrachloroethylene) along its axis. A treatment wall, strategically placed to intercept the plume, was composed of 22 percent (by weight) granular iron and the remainder coarse sand. The sand in the wall was coarser than the surrounding environment to encourage groundwater flow through the wall rather than around it. Monitoring wells were located at distances 0.5 meters up gradient to the wall, 0.5 meters and 1.0 meters in the wall, and finally, 0.5 meters down gradient of the wall.

The monitoring program involved 13 sampling events over a 475-day period. Although the majority of degradation occurred in the first 50 cm of the passive treatment wall and the performance deeper in the wall was less than expected, reductions in TCE and PCE of 95 and 91 percent respectively were observed. No vinyl chloride by-product was found in the samples, and only trace amounts of dichloroethylene (DCE) were found down gradient. However, higher than background chlorine concentrations consistent with the amount of TCE and PCE degraded were found down gradient.¹²

2. Site 2—Arctic Regions in Canada: Combined Soil Washing and Fenton's Reagent for PCBs

The Environmental Sciences Group (ESG) at the Royal Military College has been looking at ways to address PCB soil contamination on sites in the Canadian Arctic for several years. They have conducted a series of experimental laboratory tests with known technologies, thought to be potentially viable in the treatment of PCBs. The most promising non-destructive studies demonstrated to date were undertaken at two arctic sites, Resolution Island (Northwest Territories), and Saglek (LAB-2), Labrador.

¹¹ S.F. O'Hannesin, *A Field Demonstration of a Permeable Reaction Wall for the In Situ Abiotic Degradation of Halogenated Aliphatic Organic Compounds*, 1993.

¹² This case is also included in Volume I of the Institute for Defense Analyses Paper P-3383, *Environmental Restoration—Expedient Methods and Technologies: A User Guide with Case Studies*, p. 69.

Arctic sites are both remote and hard to reach, thus making the use of standard PCB remediation (such as incinerators) difficult to implement and support. The isolation, short summer season, and poor weather conditions make cleanup projects more difficult than in more temperate regions. A preliminary bench-scale result obtained by ESG indicated that the use of Fenton's reagent may be an effective method of treating PCB-impacted soils in the north and was worth further study. A field project began in Saglek and Resolution Island with sample sizes of 10–40 kg of soil contaminated with PCBs.

The field tests demonstrated up to 87-percent removal of PCBs from an arctic soil matrix contaminated with 100–200 ppm PCBs. The process involved the degradation of PCB molecules by Fenton's reagent oxidation, followed by physical separation of fine particles by decanting. In all cases the soil's organic content was less than 2 percent, so it was assumed that an insignificant portion of the reagents was lost in the degradation of non-PCB organics.

Based on the laboratory results, a testing scheme was developed to investigate the most effective method of using Fenton's reagent in the degradation of PCBs. Five different treatment methods were carried out at Saglek, including three agitated soil slurry reactors (one impeller agitated and two different size rotating drums), one unmixed reactor and finally an *in-situ* application. Hydrogen peroxide concentrations of 30 percent were used for the field experiments and a solution of 13.7 grams FeSO₄ per liter was used as the ferrous iron source.

The process involved three time-incremented liquid reagent additions, using either water or hydrogen peroxide (water was found to be an active ingredient in desorption and a good decanting fluid) in the reactor. The liquid reagents were added to soil amounts ranging from 1–40 kg. A total of 250 kg was eventually treated. Generally, 18 liters of the reagent was added to every 10 kg of soil. After each liquid addition, approximately half the volume of the reagent liquid was pumped into the reactor as iron solution over the course of 1 hour. This process was repeated three times with different combinations of reagent liquids (see Table 7).

Table 7. Time-Incremented Liquid Reagents

Treatment	1 st Liquid	2 nd Liquid	3 rd Liquid
Control	Water	Water	Water
PPP	Peroxide	Peroxide	Peroxide
PWW	Peroxide	Water	Water
WWP	Water	Water	Peroxide

The concentration of 13.7 grams FeSO_4 per liter may be too strong. In effect, the high concentration of iron solution relative to the hydrogen peroxide solution induced PCB degradation but also produced excess heat. This heat, given a lack of temperature control, actually brought some sample slurries to a boil. However, it was noted that diluting the solution to 6.8 grams FeSO_4 per liter would avoid boiling conditions without hindering or slowing PCB degradation or particle size fractionation.

Particle fractionation and decanting removed a significant percentage of the PCBs from the initial soil matrix. Smaller particles (fines) have a greater specific surface-area-to-mass ratio than do large particles and hence adsorb a greater quantity of contaminant per unit mass. Since most fines are in suspension, decanting the slurry essentially removed the suspended particles and anything adsorbed to them. In fact, after three water washes in the impeller mixed reactor, decanting alone resulted in a reduction of PCB concentration in the slurry from 200 ppm to <50 ppm. The fines recovered do require additional remediation, but at a volume that can be 75 percent less than the original.

Degradation of PCBs does occur in the process, however. Significant degradation was observed in all methods that used peroxide washing at one point in the treatment. The best results were encountered with three consecutive peroxide washings (45 percent in the impeller mixed reactor). Diminishing returns were noted with every additional hydrogen peroxide washing. One peroxide washing followed by two water washings was found to be more effective than two water washings followed by a peroxide stage. This finding also supports a degradation theory.

Degradation was estimated by mass balance, comparing the mass of PCBs removed in the control sample (three water washings) with the amount of PCBs removed from the treated samples. For the impeller mixed example of three peroxide washings, the coarse fraction of the sample was found to contain 75 percent less PCBs than the original concentration. The control sample (with three water washings) only indicated a 30 percent loss in PCB concentration. The loss demonstrated by the control sample was due to soil washing (by the water) and particle fractionation, whereas the loss of an additional 45 percent (75 percent – 30 percent) in the treated sample was due to the Fenton's reagent action.

An *in-situ* trial was also performed on 18 one-square-meter (1 m^2) plots directly on the ground. The same proportions of reagents were added to the soil as were in the impeller reactor, at similar time increments. Variations were attempted on the soil with less than 50-ppm concentrations. Three variations were used:

- Tilling the soil vs. not tilling the soil
- Adding the iron solution or not (the underlying assumption is that when the iron solution is not added the soil's natural iron content is sufficient to catalyze the reaction)
- Adding a combination of liquids.

Significant measurement errors were encountered when summarizing the data for the results in this test. However, the test developed two findings: (1) that relying solely on the soil's natural iron content is not sufficient and (2) that tilling may not be necessary given the good percolation demonstrated in arctic soils.

Surprisingly, the best removal efficiencies were observed in an unstirred, unmixed impeller reactor to which the reagents were added and treated in a similar fashion to those previously described. The boiling action caused by the Fenton's oxidation did account for some mixing in the barrel. Significant error measurements were noted, making the results suspect in some cases (for instance, some samples demonstrated a negative loss in their PCB concentration). But the results are important because they indicate that mixing the slurry may not be required.

The process of combining soil washing and the use of Fenton's reagent has some limitations that must be considered along with the results. A significant amount of waste is generated as a result of particle fractionation, a large amount of energy is required for sieving and mixing, and the volume of hydrogen peroxide required is large. Also some characteristics of arctic soils make them markedly different from soils found in more inhabited areas, where high organic content, for instance, may compete for the hydroxyl radicals.

This study has shown that there is some potential to combining soil washing and the use of Fenton's reagent in an overall process. Sieving the soils before adding reagent could significantly diminish reliance on decanting (although it could remain a final polishing step) and serve to remove a large volume of low-level contamination from coarse soil. The use of Fenton's reagent could then be limited to optimal situations such as treatment of the smaller volume of finer fractions while minimizing waste streams and reagent requirements.

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IV. HEAVY METALS

Remediation of heavy metals is a challenge. Generally speaking, if soil is contaminated, it is left where it is when it is not a threat to life or health. If it is a threat because it is contaminated with potentially toxic metal cations such as Pb^{2+} , Zn^{2+} , Cr^{3+} , Cd^{2+} , or Hg^{2+} , it is then dug, hauled, solidified, landfilled, permanently flooded, covered by a cap, or contained in a slurry wall. If the choice is made to remove heavy metal contaminated soil or sediment to a landfill, then other issues about landfill placement, design and maintenance arise, including the need for liner and caps. If water is contaminated with heavy metals, it must be treated or its use must stop. Some progress has been made in the remediation of heavy metal contaminated water in the mining industry, but the results of technology use are not consistent.

Determining the species of a metal determines its toxicity. For instance, Cr(VI) is quite toxic but Cr(II) is almost non-toxic, and generally no more than 20 percent of chrome is Cr(VI) . However, very few direct *in situ* experimental methods are available for speciation. Therefore, identifying these species (speciation) in the field and obtaining reasonable estimates of their thermodynamic and kinetic stabilities continue to puzzle environmentalists and toxicologists.

The difficulty arises because of the different valence states that metals can assume, depending on conditions such as pH, organic ligand availability, soil composition, contact with microorganisms that change valence states, and the presence of other metals. For these reasons, standards for determining risk to human health and environment have not been formally assessed for heavy metals as has the risk for petroleum contamination. However, if groundwater or soil is acidic or vulnerable to acidic conditions (such as acid rain), metals can become or are bioavailable. If human beings must contact the heavy metal directly or indirectly, such as by eating plants grown in soil that is contaminated or drinking water contaminated with heavy metals, then the contamination needs to be removed.

In cases where dig and haul is the method chosen, generally only the first 18 inches of soil need be removed if heavy metal contamination comes from surface deposits. Soil washing (treating heavy metal contaminated soil as if it were complex

laundry and using physical and aqueous chemical methods to remove contamination) is very costly, requiring extensive engineering and labor investment. For heavy metal contaminated groundwater that is pumped and used for drinking or irrigation water, the water must either be treated or its use must stop.

Generally, heavy metals of concern in Europe are chromium and arsenic. Chromium is a priority pollutant in the United States since it is known to cause cancerous mutations in laboratory animals and human beings. It is one of the most widely used metals in industry, resulting in large quantities being discharged. In contrast to most metals, chromium is usually soluble under oxidizing conditions and only limited removal can be achieved by conventional precipitation methods. Reducing hexavalent chromium to trivalent chromium detoxifies it, but the best range of reduction-oxidation (redox) potential for Cr(VI) reduction in the field has not been well established. Inorganic arsenicals such as As(V) and As(III) are very toxic. Arsine is the most toxic form of arsenic because it is a gas at ambient temperatures and pressures. One major effect of arsine is the hemolysis of red blood cells followed by kidney failure and death. Typical conditions that result in accidental arsine formation include water solutions of arsenic, an acid or base, and a metal in its elemental form. An acid sludge with arsenic in a galvanized bucket or an aluminum tank with arsenic and containing sodium hydroxide could generate arsine.

On military installations, heavy metal contamination varies, with contamination of many metal species from various operations. The most obvious location for heavy metals and by bulk the most are in firing ranges. The main concern is lead, the majority of the bulk of the bullet, with secondary contamination from the outer casings of the bullets that are made of copper and zinc.

A. CASE STUDY: SITE 1—METALLOCHEMIA INDUSTRIAL SITE IN BUDAPEST AND THE TOWN OF NAGYTÉTÉNY, HUNGARY

The local health authority stopped operation of the Metallochemia Factory in May 1990 because of the heavy metal contamination of soil in the territory and surroundings of the factory. This was the first occasion in Hungary when the activity of a factory was stopped because of the pollution it had caused.

The investigation of the pollution was conducted in the framework of the Dutch-Hungarian cooperation in environmental protection, with a grant from the Dutch Government. Intron-Bodemtech, Environmental and Geotechnical Consultant (The

Netherlands) did the work. The purpose of the investigation was to establish the horizontal and vertical extent of the contamination in soil and groundwater. On the basis of obtained results, a risk evaluation was made with respect to public health and environment.

Note that near the Metallochemica Industrial Site there are private gardens and fields where families grow crops for eating.

Based on risk evaluation it can be stated that:

- Within 1000 meters from the center of the Metallochemica, there is an actual risk for children with respect to lead, whether or not they eat food grown in the area.
- When privately grown crops are consumed (assuming 100-percent self-support), an actual risk to lead is present for both children and adults to at least 1500 meters from the center of Metallochemica. The risk for children is a multiple of that for adults.
- The ground water quality is such that it is not fit for human consumption.

To remove the actual risk for public health with respect to lead in the area around Metallochemica, a soil cleanup or rehabilitation operation had to be undertaken.

On the basis of the obtained results, Hungarian companies have worked out several remedial measures. Due largely to the lack of money, the cleanup work has not been started so far.

The Metallochemica plant is located on a 20-hectare site in the southern part of Budapest. The plant began operation in 1910 with the refining of lead-containing materials. Later, copper electrolysis and melting were carried out. The basic technological processes were black-copper technology, chrome-alum manufacturing technology, production of lead articles and copper alloys, and recovery of battery wastes.

Due to protests of the people living nearby, investigations were carried out in the mid-1980s to determine the level of ground and groundwater contamination. These investigations indicated that Metallochemica and its surroundings are highly contaminated. In May 1990, the local health authority stopped all activity at the factory.

In the framework of the Dutch-Hungarian environmental protection cooperation, the Dutch government gave a grant to carry out a determinative investigation at the

Metallochemia site and its surroundings in 1990. Intron-Bodemtech, Environmental and Geotechnical Consultant (The Netherlands) conducted the work.

The investigation area was divided into three subareas:

1. Metallochemia work plant with an area of 11.5 hectares
2. Metallochemia dumpsite with an area of 9.0 hectares, where approximately 220,000 m³ of slag and other waste materials are stored
3. Surroundings of Metallochemia with a radius of approximately 1500 meters, resulting an area of just over 7 km².

1. Geology and Hydrogeology

The affected area is on the Danube floodplain. This floodplain is the result of structural movements, which took place at the end of the Pleistocene/Holocene geological age. The surface is covered with a clay-silt layer of Holocene age. The thickness of this layer is between 1.0–2.5 meters. The clay-silt is overlying sand-gravel and gravely sand deposits of Pleistocene age. Local sand lenses are between the clay-silt and sand-gravel layer. The thickness of these layers is 8–10 meters. Underneath these Pleistocene age layers are sand, sand-clay, and clay-marls of Upper Pannonian geological age.

Groundwater level is influenced by precipitation and the water level of the Danube. During the period of average and maximum Danube water level, the groundwater flow is directed toward the Danube. During maximum water levels, the Danube will infiltrate the lower part of the flood plain. The maximum distance of direct influence of the Danube is estimated as approximately 900 meters.

2. Results of the Investigation

a. Metallochemia Dumpsite

About 200,000 m³ of waste material is present at the dumpsite. Waste materials consist of lead and zinc (80 percent), copper (14 percent), and tin (3 percent). These metals are incorporated in slag and other buried waste. The amount of copper in the composition of the slag is about 1 percent; the amount of lead is about 3 percent.

The clay-silt layer appears to be present underneath the whole dumpsite, although in the older part its thickness declines to 1.5 meters. At the southern, younger part, neither lead nor zinc has penetrated the clay-silt layer significantly, while at the northern, older part, both lead and zinc have penetrated this layer. Here, the penetration of lead is

restricted to the upper 1.0 meters. Zinc has penetrated the clay-silt, while cadmium has not.

The northern part of the dump has direct contact between waste material and groundwater for longer periods. Direct contact in the southern part will occur only during very high groundwater levels and then the contact time will be relatively short. On average, about 30 percent of the dump will be in direct contact with groundwater.

The contaminants in the groundwater underneath the dump are zinc, cadmium, sulphides, phenols, and, to a smaller extent, lead. The extent of groundwater contamination is limited to the area of Metallochemia.

b. Metallochemia Plant

At the Metallochemia plant, the top of the clay-silt layer has been excavated and replaced by a sand, debris, slag, and cinder back-fill. This back-fill has a maximum-recorded thickness of approximately 2 meters. At most locations, the backfill is covered with concrete. This concrete cover prevents direct contact and diverts much of the rainwater from the backfill.

The quality of the soil underneath the backfill layer has not been determined, but the situation is more or less comparable to the southern part of the dump. The penetration of heavy metals in the clay-silt is expected to be rather limited.

There are indications that the backfill at the center of the plant will never be in direct contact with groundwater. In other parts, contact occurs when groundwater level is near maximum.

c. Surroundings of Metallochemia

In soil, lead is the most decisive contaminant. The center of contamination is located between 250–600 meters east to southeast of Metallochemia in the direction of prevailing winds. On average, the 150 mg Pb/kg contour line can be expected to be situated somewhere between 1250–1400 meters southeast from the center of Metallochemia.

For lead as well as cadmium, a distinct decrease in depth has been established to approximately the 0.6-meter level. Below the 0.6-meter level, no significant decrease is found, with the exception of some local spots in the center of contamination.

Approximately 108,000 m³ of soil is contaminated with lead in concentration of 600 mg Pb/kg, approximately 155,000 m³ of soil with 250–600 mg Pb/kg and 130,000 m³ with lead in concentrations ranging from 150–250 mg Pb/kg.

3. Cleanup and Rehabilitation Measures

Based on location, type, and extent of contamination, restoring the multifunctionality of the area will probably not be possible with current practices and technology.

In case of the Metallochemia area, isolation is to be considered as the optimum rehabilitation method. A civil-technical isolation can consist of the following elements:

- Placing an impermeable cover layer on the surface of the dump
- Installing a cut-off wall around the Metallochemia area, fencing off the horizontal groundwater flow in the water bearing layer
- Extracting and cleaning groundwater within the isolated area.

In the surroundings of Metallochemia, and especially in the town of Nagytétény, the removal of the contaminated soil seems to be the best solution. The removed contaminated soil can put on the surface of the dumpsite.

Before starting the rehabilitation activities, a number of interim measurements can be taken, aiming to reduce the existing risk for public health:

- Privately grown crops from the zone around Metallochemia where lead concentrations higher than 150 mg Pb/kg have been found, should not be eaten.
- Contaminated dust should be removed at Metallochemia and in the town of Nagytétény.
- Groundwater in the area should not be used for human consumption.
- Irrigation of crops with groundwater taken near the sewerage system and west of Metallochemia should be avoided.
- Crops grown on a commercial basis in the area west of Metallochemia should be inspected to establish their possible contamination.

For solving the problem, approximately 2.0 billion Hungarian Forint (US\$ 10 million) are needed. This is more than the market value of the site of Metallochemia factory.

B. CASE STUDY: SITE 2—HANDLING OF LEAD-CONTAMINATED SOIL AND SCRAP METAL FROM SMALL ARMS FIRING RANGES IN SWEDEN

The Swedish Armed Forces control about 400 firing ranges with backstops (berms). These berms consist of mixed sand and gravel material with, in some cases, a layer of sawdust on the top. Bullet material accumulates in these berms. The amount of contaminated berm material is estimated at 100,000 m³.

The Swedish Armed Forces also have about 80 areas used for open firing ranges. Although bullet fragments spread over large areas, concentrated amounts of heavy metals are found in areas with natural berms and in target areas. "Hot spots" are areas in these open ranges where the amount of lead is so great that cleanup is necessary. The amount of contaminated soil from the "hot spots" is estimated at 100,000 m³.

Whether bullets are in berms or in the free-range "hot spots," they are found whole (though distorted from firing) or fragmented. Bullets may be of different types. On average, bullets are 50-percent lead, 45-percent steel, and 5-percent brass or copper.

The Swedish National Environmental Protection Agency Report 4638 set standard contents for heavy metal polluted soil, measured in milligrams of metal per kilo of dried soil (mg/TS). For less sensitive soil and groundwater protection (classified as MKM GW), the maximum lead content is 300 mg/TS and maximum copper content is 200 mg/TS. Theoretically, at least 100 bullets per square meter are needed for the lead content to reach the maximum allowed value. Finding such a high concentration of lead is very unusual, even at firing ranges with a long history of intensive use.

Measurements are made with soil samples, with an x-ray fluorescent instrument XRF, or another type of metal detector. The armed forces use the XRF instrument and collect control soil samples for analyses to confirm the XRF findings. Tests using the ordinary metal detector are also made to see if the detector registers when more than 300 mg/TS are in the test sample, and this method has proved rather reliable.

Lead content at firing range berms that have been used for a few years are in the high range: 5,000–50,000 mg/TS is not unusual. Leaching of lead into the soil is very slow, even in an acid environment. At a depth of 50 cm, soil in the berm is the same as nearby uncontaminated soil, even if the firing range has been in use for 15–20 years. Therefore, berms are dug to a depth of 60 cm and the excavated soil is treated. If a range has a history of having soil added to the top of the berm material, soil material is

excavated to 150-cm depth. With control measurements of lead content during the excavation, the amount of soil mass can be minimized and thus help contain costs.

Free range "hot spots" that consist of sand, gravel, or moraine can be cleaned with the same process. If humus or very fine material is present in the "hot spot," the cleanup may need to include adding lime to increase the pH, depositing, or some other method. These other methods are not included here.

Cleanup using the process described below creates three outputs: soil that is 200 mg/Ts or less, lead slurry/sludge, and "pure" lead. Since processed soil may still have up to 200 mg/Ts in it, it must be used in a controlled manner. For instance, the soil can be used in new firing range berms, including environmental berms that capture whole bullets with a rubber granulate with tight cloths. The cleaned soil can also be used as backfill, ballast in concrete, road gravel, and so forth, in areas that are classified as MKM GW. The residual lead slurry/sludge with 100,000–500,000 mg/Ts must be deposited in an approved depot. Possibly the slurry/sludge may be deposited in the form of additive to concrete in well-defined building projects, which, in the foreseeable future, will lie in insensitive ground, for instance, bridges and dams. Pure lead in the form of whole or fragmented bullets can be reused and recycled.

The current lead cleanup method is outlined below. Individual contractors may have some variations to this method.

1. Contaminated soil is fed into a station with separation of contaminated soil parts coarser than 50 mm or 124 mm. A belt balance is installed for control and registration of the fed amount of contaminated soil.
2. Soil greater than 20 mm is sifted away. The 0–20 mm material goes to a drum-washer where the material is treated to separate particles from each other and to have clean particle surfaces. At the end of the drum washer is a drum sieve to separate 0–2 mm sand.
3. Magnetic material (such as enveloped bullets) in the 2–20 mm fraction is separated by a ballistic magnetic separator and conveyor. After that, pure lead is separated by means of an all-metal separator.
4. Fine material from the drum sieve is treated in a magnetic separator for separation of magnetic material. The lead particles continue in the process.
5. The large lead particles are then separated in a spiral package.

6. The light product from the spiral package is transported to a flotation bank for separation of fine lead particles. The material is conditioned before flotation. The discharge from the flotation constitutes the pure product, from which water is removed by a screw dewaterer. The sand is loaded into a special container that soaks the sand further so that it becomes easier to handle.
7. The overflow from the screw system and the concentrate from the flotation are pumped into a clarification thickener. The water is recycled for recirculation in the process.
8. The slurry/sludge from the clarification thickener is further soaked in a straining belt press. The press water from the filter is pumped to the clarification thickener.

Experiments to replace the lead slurry/sludge steps with some form of chemical precipitation are in progress. It will probably not reduce costs or the need for machines, but increase how clean the soil becomes. The whole process requires large units with large areas, and all discharges and emissions must be securely controlled. Therefore, the installation cost is high, at least 250,000 Swedish Krona (SEK) (US\$ 29,000), which in turn requires large amounts to clean to obtain an acceptable price per unit volume. Placement of a heavy metal cleanup station should be available to clean at least 4000 m³. However, transportation costs to the cleanup unit need to be considered. After installation, the cleaning cost is 400 SEK (US\$ 46) per ton or 300 SEK (US\$ 35) per cubic meter. The capacity is 50–150 m³/day of soil.

Including installation and transport costs, the cost is about 900 SEK (U.S. \$105 as of March 2000) per cubic meter for areas of an appropriate size. Table 8 illustrates small arms restoration projects in Sweden.

Table 7. Small Arms Restoration in Sweden

Year	m ³ of Soil	Number of Berms/ "Hot Spots"	Location	Cost per m ³ SEK/USD	Tons of Pure Lead	Use of Cleaned Soil
1997	4,900	17	Värmland	750/87	80	In berms or parking lot
1998	5,300	7/many	Örebro	675/78	85	In berms
1999	6300	18	Östergötland	750/87	95	In berms
1999	11,000	38	Boden and Luleå	865/100	180	In berms or firing range roads

In 1999, work began on cleaning another three areas. In 2000, three new areas are subject to procurement and another two are planned. In 2001 to 2004, Swedish Armed Forces plan to clean the rest of the berms. From 2005 forward, previously cleaned berms that have not been rebuilt into environmental berms will be cleaned and rebuilt.

The work of cleanup is complicated and controlled by environmental authorities. Therefore there is a long handling time before the process can start. Five or six companies at present meet the requirements of the Swedish Armed Forces for berm and "hot spot" cleanup. The chemical cleaning mentioned above can simplify the handling of surplus masses. Improved measuring methods for heavy metals can define exactly the amount of contamination and the need for new soil cleanup and by that reduce the cost.

The whole cleanup activity is coordinated from a central level, and carried out on a local level after letting each contract.

C. CASE STUDY: SITE 3—FORMER CANADIAN FORCES BASE CHILLIWACK PHYTOREMEDIATION PROJECT

Phytoremediation is defined as the *in situ* use of plants to stabilize, remediate, reduce, or restore contaminated sites, taking advantage of plants' natural abilities to take up, accumulate, and/or degrade constituents of their soil and water environments. With a drive to advance new environmental remediation technologies, the Environmental Sciences Group at the Royal Military College (RMC) developed a multi-year strategy using phytoremediation to remediate 7,500 m³ of lead and copper contaminated soil from a 300-meter rifle range at former CFB Chilliwack. The Department of National Defence and Environment Canada is funding the project. The first field trial season was completed in 1999. Laboratory analyses and greenhouse experimentation results are not available as of this printing.

CFB Chilliwack has been in operation since 1942 and was targeted for closure in 1995. During its years of operation, the base provided year-round training for military engineers. The 300-meter range is on land partly owned by DND and partly leased to DND by a private citizen necessitating the relocation of the contaminated soil prior to remediation. In 1996, the range soil was excavated and stockpiled on site. Sample analyses showed that the stockpiled soil contained elevated levels of lead and copper. Average concentration of lead was 943 ppm (maximum 3,700 ppm), and average concentration of copper was 187 ppm (maximum 740 ppm). In the spring of 1999, the

soil was relocated to a training area where the phytoremediation project is currently underway.

1. Project Design

One of the primary considerations in project design was to protect the surrounding native soil from migrating contaminants. Therefore, the experimental area was designed with a double layer geomembrane, which effectively encapsulates the contaminated soil. A 'run-off' containment trench was also integrated into the design to contain run-off water from the plots. Although the soil had previously tested negative for lead leachate, the addition of chelating agents in the experimental stages necessitated continuous water monitoring before being discharged back into the environment. The containment cell, in which the experimental plots are situated, allows for lead movement to be monitored throughout the experiment.

The soil was sieved to remove bullet fragments and large particulate matter, and then graded into the experimental area. The experimental area was divided into 16 plots measuring 6 x 6 meters each. The plots were separated using a ¼-inch plexi-glass barrier. All 16 plots were amended with 10 percent peat moss and treated with an industrial grade 28-10-10 fertilizer. One plot was the control plot. The remaining 15 plots were divided into three sets of five plots, with one of three different chelators (one synthetic and two organic) applied to a set of five. Four of the plots in each treatment contained one or more plant types and one plot was left as a treatment control. The plant species used in the experiment were *Phragmites australis*, *Equisetum arvense* (horsetail), *Brassica juncea* (Indian mustard), *Pisum sativum* (garden pea) and four *Pelargonium* (geranium) varieties. Planting took place in late June and harvesting in mid-October 1999. Throughout the summer, an irrigation system was used to maintain soil moisture during dry periods. During the harvest in October, two large composters were built on site. These composters were fitted with a plastic liner to contain any lead contamination as the plant matter breaks down over the winter period. The large, unlined, unplanted section of the compound will be planted in the spring of 2000 with the species deemed most effective from the first year of research.

The primary goal of this project is to track where the lead is present throughout the growing process. Mass balance is important in determining if the lead remains accessible to the plants throughout the growing period or if the addition of synthetic and organic chelators allows the lead to move away from the plants' root zone. The calculation of mass balance becomes more feasible when analysis is completed within a

contained area. To this end, greenhouse experiments are currently being conducted at RMC under extremely controlled conditions.

2. Preliminary Interpretation of Incoming Data

The plant data analyzed to date (April 2000) indicates that all eight plant species have, to some degree, accumulated both lead and copper in their tissues. The four geranium species have shown the greatest biomass accumulation and, comparatively, the shoots of the plant held a much larger percentage of this biomass. The degree of contaminant reduction in the soil is not clear as analyses are ongoing. It is, however, encouraging to see that the contaminants are indeed being extracted from the soil. Actual volume calculations will be carried out pending completion of data analyses. Cost data are not included.

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Appendix A

RELEVANT WORLD WIDE WEB SITES

Appendix A

RELEVANT WORLD WIDE WEB SITES

This web site list is limited to a few excellent sites that are extensively linked to other related web sites. The reader is strongly encouraged to explore these for additional information.

A. NICOLE—THE NETWORK FOR INDUSTRIALLY CONTAMINATED LAND IN EUROPE

<http://www.nicole.org/>

NICOLE is the principal forum that European business uses to develop and influence the state of the art in contaminated land management in Europe. The overall objective of NICOLE is to pro-actively develop, enhance and communicate concepts/strategies and technologies for the responsible management of soil and groundwater problems, which enable a balance amongst risk reduction, environmental merit, costs and time.

<http://www.nicole.org/nicole2/weblinks/NICOLElinks.shtml>

Especially note that there are 135 or so links to other relevant sites in 18 countries, global regions, or global networks.

B. THE RISK ABATEMENT CENTER FOR CENTRAL AND EASTERN EUROPE (RACE)

<http://www.nicole.org/RACE.shtml>

RACE is an international cooperative research, education and training institution that develops and puts into practice risk management methods and new technologies to solve environmental problems. RACE acts as a forum and clearinghouse to facilitate cooperation, exchange information and experience, and to educate and train professionals.

Located in Katowice, Poland, RACE was created in 1996 in response to a critical need for comprehensive and cost effective environmental management in Central and Eastern Europe (CEE). In conjunction with careful consideration of social, economic and legal factors, RACE promotes the use of scientific risk assessment methods and innovative

technologies as essential tools to decide priorities and effectively use resources in managing the CEE environment.

C. ENVIRONMENT CANADA SCIENCE AND TECHNOLOGY WEB SITE

http://www.ec.gc.ca/scitech/index_e.htm

(Note the underscore line in this address: ".../index_e.htm")

Environment Canada's Science and Technology Web Site is dedicated to sharing information on Environment Canada's science and technology, as well as policies and approaches used to manage science and technology.

D. BEST ENVIRONMENTAL DIRECTORIES

<http://www.ulb.ac.be/ceese/meta/cds.html>

This site contains a selection of the best Internet environmental directories for more than 500 environmental subjects.

E. THE WORLD-WIDE WEB VIRTUAL LIBRARY-ENVIRONMENT

<http://earthsystems.org/Environment.shtml>

Provides a searchable index of more than 1,000 environmental resources arranged alphabetically and by category. Subjects are Biodiversity and Ecology, Earth Sciences, Energy, Environmental Law, Forestry, Landscape Architecture, Meteorology, Oceanography and Sustainable Development.

F. THE GLOBAL NETWORK OF ENVIRONMENT AND TECHNOLOGY

<http://www.gnet.org/>

GNET is an award-winning environmental technology, news and business center that promotes the use of innovative environmental technologies. This site is made possible by a cooperative agreement from the National Energy Technology Laboratory and the Department of Energy's Office of Science and Technology in the United States.

G. MAPS AT ESRI, ESRI INTERNATIONAL, AND GIS.COM

Explore live Internet Map Server demonstrations at:

<http://maps.esri.com/>

<http://gis.esri.com/intldist/contactint.cfm>

ESRI International — This page was developed to provide people outside the United States with links directly to items pertinent to them.

<http://www.gis.com>

GIS.COM is a source of information and advice on all aspects of Geographical Information Systems and is maintained by ESRI.

H. THE REGIONAL ENVIRONMENTAL CENTER FOR CENTRAL AND EASTERN EUROPE

<http://www.rec.org/Default.shtml>

The Regional Environmental Center for Central and Eastern Europe (REC) is a non-advocacy, not-for-profit organization with the mission to assist in solving environmental problems in Central and Eastern Europe (CEE). The Center fulfils its mission through encouraging cooperation among non-governmental organizations, governments and businesses, supporting the free exchange of information and promoting public participation in environmental decision-making.

I. CENTER FOR ECONOMIC AND SOCIAL STUDIES ON THE ENVIRONMENT (CESSE)

<http://www.ulb.ac.be/ceese/english/indexuk.htm>

The CESSE was created following the first United Nations Conference on human environment, which was held in Stockholm in 1972. It is made up of a pluri-disciplinary research team that devotes its activities to the qualitative and quantitative evaluation of economic-environmental interactions.

Research carried out concerns mainly the following areas:

- Indicators of sustainable development;
- Environmental meta-database;
- Damage cost to the environment and health (externalities);
- Study of mobility and its impacts;
- Cost-benefit analysis, the cost-effectiveness analysis.

J. OVAM - PUBLIC WASTE AGENCY OF FLANDERS

<http://www.ovam.be/>

Although this site is specific to Flanders, it includes a searchable database as well as the related links included in the page below.

<http://www.ovam.be/internetrefs/english.htm>

One of the greatest environmental guidelines to the WWW, this site attempts to link only to non-commercial environment related sites covering specific topics and is updated several times a month.

K. EUROPEAN ENVIRONMENT AGENCY

<http://www.eea.eu.int/>

Considered Europe's gateway to environmental information, this site is maintained by the European Environment Agency and EIONET partners.

<http://service.eea.eu.int/>

The "Service Section" offers various tools to search and retrieve general and specific environmental information, using the themes of the "Theme Section". The "Search Section" includes both standard and multilingual search facilities to search in the full text index of this site and some other sites. The "EIONET Section" can be used as a gateway to national environmental information.

L. ENVIRONMENTAL ROUTENET OF CAMBRIDGE SCIENTIFIC ABSTRACTS

<http://www.csa.com/routenet/>

Environmental RouteNet is a fee-based gateway to the world's foremost databases and information sources available via the Internet. The service includes searchable links to hundreds of carefully screened environmentally-related resources, selected and indexed by the editors at Cambridge Scientific Abstracts. In addition, the site provides access to proprietary environmentally-related databases and to daily updates of environmentally-related news stories, regulations and legislation, plus much, much more.

M. CENTER FOR SUBSURFACE MODELING SUPPORT

<http://www.epa.gov/ada/csmos.html>

The site includes FREE downloadable ground water related software packages.

The Center for Subsurface Modeling Support, or CSMoS, provides a source for publicly available ground water and vadose zone modeling software and services. CSMoS was established in 1989 to provide a focal point for the distribution of models and databases developed through in-

house and extramural research activities, to provide technical support for these models and databases, and to provide review of model applications at hazardous waste sites.

**N. THE FEDERAL ENVIRONMENTAL AGENCY OF GERMANY
(UMWELTBUNDESAMT)**

<http://www.umweltbundesamt.de/index-e.htm>

This searchable site of the Environmental Agency of Germany includes access to the bibliography of more than 500,000 books, articles and microfiche in the scientific library, as well as events, facts, exhibitions and annual reports.

O. THE NORTH ATLANTIC TREATY ORGANIZATION (NATO)

<http://www.nato.int/ccms/home.htm>

At the web site, open Pilot Studies.

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Appendix B
ACRONYMS

Appendix B

ACRONYMS

As	arsenic
BH	bore hole
BTEX	benzene, toluene, ethylbenzene and xylenes (metha-, ortho-, and para-)
Cd	cadmium
CFB	Canadian Forces Base
CH	chlorinated hydrocarbons
CHC	chlorinated hydrocarbons
CK	Czech Koruna
cm	centimeter
cm/sec	centimeter per second
C of A	Certificate of Approval
CO ₂	carbon dioxide
Cr	chromium
Cr(III)	trivalent chromium
Cr(VI)	hexavalent chromium
Cr ⁺⁶	chromate
CT	carbon tetrachloride
Cu	copper
DCE	dichloroethene
DDT	1,1,1-trichlor, 2-2 bis-(p-chlorphenyl) ethane
DNAPL	dense non-aqueous phase liquid
DND	Department of National Defence (Canada)
DWO	drinking water objective
EDB	ethylene dibromide
ESG	Environmental Sciences Group
ETDS	electro-thermal dynamic stripping
F&G	funnel and gate
Fe	iron
FFTA	fire fighter training area
ft ²	square feet

ft ³	cubic feet
GAC	granular activated carbon
GC	gas chromatography
GLR	Gas Liquid Reactor
HC	hydrocarbon
HDPE	high density polyethylene
Hg	mercury
hp	horsepower
kg	kilogram
L	liter
LEL	lower explosive limit
LNAPL	light non-aqueous phase liquid
LPH	liquid phase hydrocarbons
LTA	land treatment area
LTTD	Low Temperature Thermal Desorption
LTU	land treatment unit
m ³	cubic meter
mg	milligram
mg/kg	milligrams per kilogram
mg/TS	milligrams per kilo of dried soil (Sweden)
Mhz	megahertz
MKM	less sensitive land use, without ground water (Sweden)
MKM(GW)	less sensitive land use, with ground water (Sweden)
MS	mass spectrometry
NAPL	non-aqueous phase liquid
NATO	North Atlantic Treaty Organization
NICOLE	Network of Industrially Contaminated Land in Europe
ORC	oxygen releasing compound
PAH	polynuclear aromatic hydrocarbons or polycyclic aromatic hydrocarbons; polyaromatic hydrocarbons
Pb	lead
PCB	poly-chlorinated biphenyls
PCE	tetrachloroethene from it's synonym "per chloro ethene," to distinguish this compound from TCE
POL	petroleum, oil, lubricants
ppb	parts per billion

ppm	parts per million
ppmv	parts per million by volume
ppt	parts per trillion
PVC	polyvinyl chloride
RACE	Risk Abatement Center for Central and Eastern Europe
RNA	remediation through natural attenuation
scfm	standard cubic feet per minute
sec	second
SEK	Swedish Krona
SVE	soil vapor extraction
SVOC	semi volatile organic carbon
TCE	trichloroethylene
TPH	total petroleum hydrocarbons
VES	vapor extraction system
VISITT	Vendor Information System for Innovative Treatment Technologies
VOC	volatile organic compound
µg	micrograms
µg/mL	micrograms per milliliter

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Appendix C

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Estonia

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Georgia

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Ministry of Defence
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Budapest
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Ministry of Environment
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H-1384, Budapest
Hungary

ATTN: Dr. Pál Varga, Deputy Director 1

OMFB, National Committee for Technological Development
Szervita ter 8
Budapest 1052
Hungary

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Evgenija Monogarova
Ministry Of Environmental And Natural Resources
Dostik St. 85
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Lithuania

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Panevecys Region Environmental Protection
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5319 Panevecys
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Liepu st. 11
5800 Klaipeda
Lithuania

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1

Vilnius Gediminas Technical University
Environmental Protection Department
Sauetekio al. 11
2040 Vilnius
Ozo g.7-8
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The Netherlands

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Norway

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Oslo MIL/Akershus
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Norway

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Norwegian Defence Research Establishment
P.O. Box 25
N-2027 Kjeller
Norway

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Dr. Jens Laugesen
Det Norske Veritas
Environmental Advisory Services
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Lt Col. Asgeir Kvam Chief of Base Management Group	1
Maj. Tor Melvold Environmental Officer	1

HQ Defence Command Norway
Navy Staff Planning Division
Oslo MIL/Huseby
N-0016 Oslo
Norway

ATTN: Cdr. Per Naess	1
Mr. Per Siem	1

Poland

Military University of Technology
Institute of Chemistry and Defence Against Chemical Warfare Agents
Kaliskiego street 2
00-908 Warsaw 49
Poland

ATTN: Col. Slawomir Neffe, Ph.D.	1
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Ministry of Interior Affairs and Administration
Public Administration Department
5/7 Batorego str.
02-591 Warsaw
Poland

ATTN: Malgorzata Sodul	1
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Institute for Ecology of Industrial Areas
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40-833 Katowice
Poland

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Poland

ATTN: Stanislaw Wilczkowiak

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Col Marek Malecki
Department of Research and Development
Ministry of National Defence
218 Niepodleglosci Ave.
00-911 Warsaw
Poland

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Portugal

Maj. José Marcos G. Gouvela
Direcção Geral de Infra-Estructuras
Ministerio da Defesa Nacional
Avenida Ilha da Madeira, 14
1400 Lisbon
Portugal

1

Republic of Moldova

Mr. Sergiu Galitchii
Head of Operative Informational System
State Ecological Inspectorate of the Republic of Moldova
Bd.Stefan cel Mare, 73
MD 2001 Chisinau
Republic of Moldova

1

Russia

Ministry of Defence
19 Znamenka
103 160 Moscow
Russia

ATTN: Viktor Sheremetev
Sergej Nikolaiwitsch Bucharin
Vyacheslav A. Nikiforov

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State Committee of the Russian Federation on Environmental Protection
Bolschaja Grusinskaja str. 4/6
123812 Moscow
Russia

ATTN: Nikolaj B. Nefedjev 1

Slovak Republic

Ministry of Defence
Kutuzovova 8
83247 Bratislava
Slovak Republic

ATTN: Lubomir Kusnir 1

Ministry of Defence of the Slovak Republic
Depart. of Environment
Kutuzovova 8
83247 Bratislava
Slovak Republic

ATTN: Renata Ondrejcakova 1

Sweden

Swedish Armed Forces Headquarters
Environmental Section
HKv / Milj
S-10785 Stockholm
Sweden

ATTN: Col. Lennart Wiman 1

Slava Blaha 1

Swedish Fortifications Administration
S - 631 89 Eskilstuna
Sweden

ATTN: Folke Borgh 1

Dr. Mats S. Ahlberg 1

Director of Research
Defence Research Establishment
FOA 4
S-901 82 UMEÅ
Stockholm
Sweden

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The Swedish Defence Materiel Administration
Weapons Directorate
SE-115 88 Stockholm
Sweden

ATTN: Mr. Bengt Stromstedt	1
Environmental Manager	
Ms. Hanna Hörnström	1
Ms. Anette Svensson	1

Ukraine

Ministry for Environmental Protection and Nuclear Safety
5 Khreshchatyk str.
252601 Kiev 1
Ukraine

ATTN: Nina Tudel	1
------------------	---

United Kingdom

European Office of Aerospace Research and Development (EOARD)
223/231 Old Marylebone Rd
London NW1 5TH
UK

ATTN: Mark Smith	1
------------------	---

Mr. Richard Owen	1
Project Manager	
Defence Evaluation and Research Agency	
Demil, Room 23, Building 106	
Porton Down, Salisbury	
Wiltshire SP4 OJQ	
United Kingdom	

Dr. Jay Patel	1
Mechanical Sciences Sector	
Defence Evaluation and Research Agency	
Room G.067, A.7 Building	
Ively Road	
Farnborough Hants, GU14 OLX,	
United Kingdom	

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Mr. Stephen James Wilkinson
Higher Scientific Officer
Defence Evaluation and Research Agency
Fort Halstead
Sevenoaks, Kent TN14 7BP
United Kingdom

1

Ministry of Defence
St. Giles' Court
1-13 St Giles High Street
London WC2H 8LD
United Kingdom

ATTN: Dr. David Liddy
Directorate of Safety, Environment and Fire Policy

Dr. Greg Marshall
Directory of Safety, Environment and Fire Policy
Room 717

1

1

Uzbekistan

State Committee for Science and Technology
29, Kh. Suleimanova Street
700017 Tashkent
Uzbekistan

ATTN: Dr. Erkin Zakhidov
Head of the Department for International Scientific
and Technological Cooperation

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